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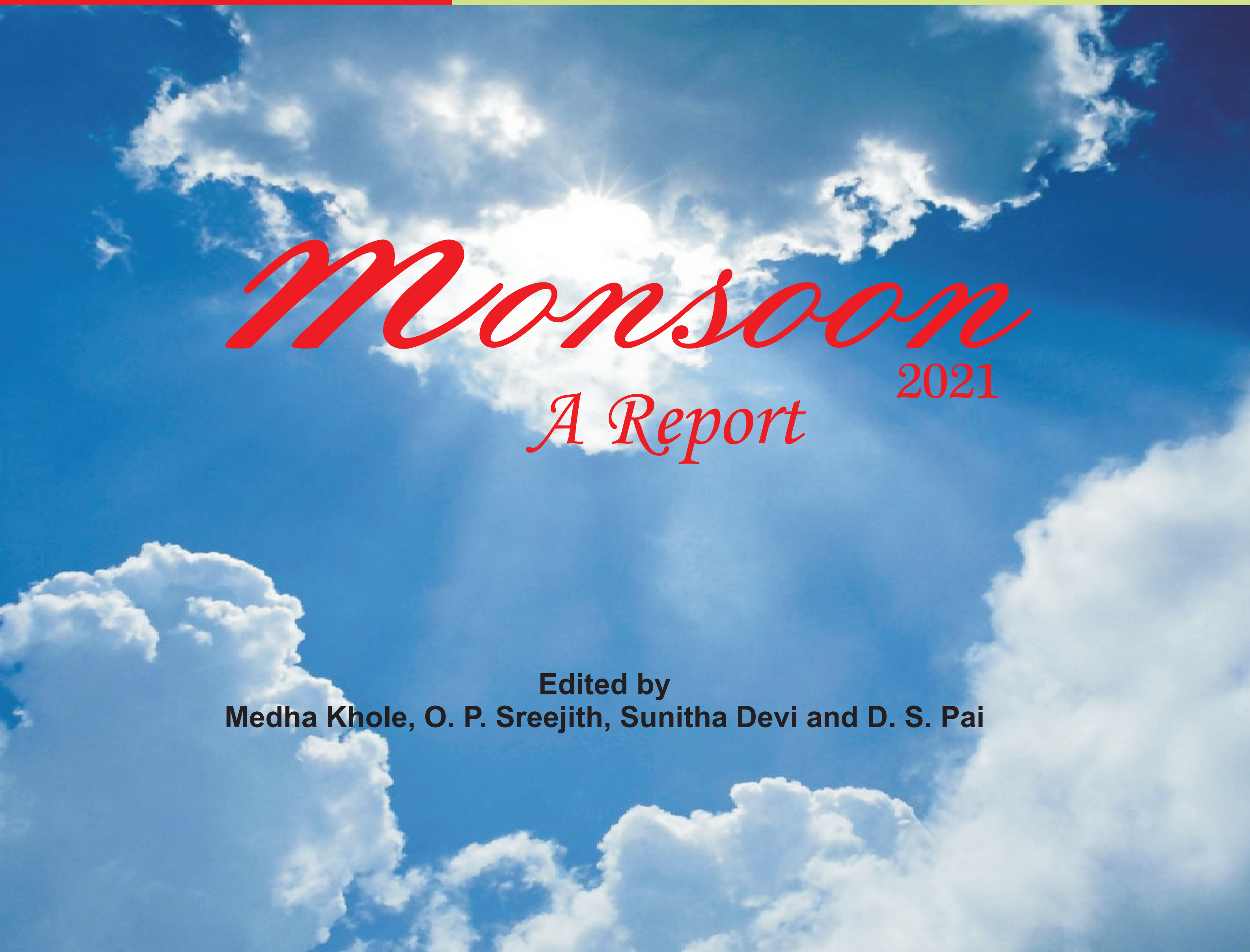

Monsoon 2021
A Report

Edited by
Medha Khole, O. P. Sreejith, Sunitha Devi and D. S. Pai

CLIMATE RESEARCH AND SERVICES
INDIA METEOROLOGICAL DEPARTMENT
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Meteorological features associated with floods over eastern India during southwestmonsoon 2020.	Office of Regional Meteorological Centre, Kolkata.
Disastrous Weather Event over Parts of Madhya Pradesh.	Office of Regional Meteorological Centre, Nagpur
South West Monsoon 2021 Over Maharashtra, Goa and Gujarat.	Office of Regional Meteorological Centre, Mumbai.
Meteorological features associated with flood over Eastern India during southwest monsoon 2021.	Office of Regional Meteorological Centre, Kolkata.
The heavy rainfall episode over Assam and Meghalaya during 28-30 June 2021.	Office of Regional Meteorological Centre, Guwahati.
Extremely Heavy Rainfall occurrences over the Southern Peninsular region.	Office of Regional Meteorological Centre, Chennai.
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Verification of heavy rainfall warning over Meteorological Sub-division	India Meteorological Department, New Delhi.
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Marine Weather Forecasting during Summer Monsoon Season	Neetha K Gopal and Coauthors
Summary and Conclusions	Medha Khole, O. P. Sreejith, and D.S. Pai. Climate Research and Services, Pune.
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PREFACE

The food security of the country largely depends on the performance of Southwest Monsoon because about 55% of the total cultivated area in India is under rain fed agriculture. The Southwest Monsoon is the principal rainy season for India. More than 75 percent of India's annual rainfall occurs during southwest monsoon season. About 70 percent of the Indian population depends on farming for its livelihood. In addition to agriculture and drinking water, the Southwest monsoon rainfall is also the essential source of water for other sectors like power and industries which are directly or indirectly influenced by monsoon rainfall. Thus, the performance of Southwest monsoon holds the key for the Indian Economy.

Since 2005, India Meteorological Department publishes a detailed report on monsoon every year to document various characteristics of monsoon in order to serve as a quick reference to both operational and research communities. The present report on Southwest Monsoon of 2021 has documented salient features of the Southwest monsoon 2021. The report has been divided into 13 Chapters which highlight various features like onset and withdrawal of monsoon, features of synoptic systems formed over the Indian Region during the season, large-scale and regional circulation features and description of meteorological analysis of significant weather events over different parts of the country, among others. It also covers forecast verification at various time scales like seasonal and extended range.

The rainfall features observed during 2021 monsoon season were described in Chapter 4. The Southwest Monsoon season rainfall over the country as a whole during 2021 was normal (99% of Long Period Average (LPA)). Rainfall distribution was generally well distributed over major parts of the country. The SW monsoon season observed significant intra seasonal variations in rainfall as realized rainfall in June (110 % of LPA), July (93 % of LPA) and August (76 % of LPA) while it was the highest during September (135 % of LPA). The homogeneous regions of Northwest India (96% of LPA) and Central India (104% of LPA) received normal rainfall. However, South Peninsula (111% of LPA) received above normal rainfall, while the homogeneous region of East & Northeast India (88% of LPA) received below normal rainfall. Out of the total 36 meteorological subdivisions, 20 subdivisions constituting 58% of the total area of the country received normal seasonal rainfall, 10 subdivisions received excess rainfall (25% of the total area) and 6 subdivisions (17% of the total area) received deficient season rainfall.

The Southwest monsoon current arrived over the south Andaman Sea and Nicobar Islands on 21st May 2021. Southwest monsoon set in over Kerala on 3rd June, 4 days delay in onset than normal. Gradual advancement of monsoon happened over many places up to central India. Monsoon covered the entire country on 13th July 2021; 8 days delay in its normal date (8th July). The withdrawal of the monsoon from western parts of northwest India started on 6th October 2021 against the normal date of 17th September with a delay of around 19 days. The Southwest Monsoon withdrew from the entire country on 25th October 2021. During end of the season, two Cyclonic Storms "GULAB" (24 -28 September) and Severe cyclonic storm "SHAHEEN" (30th September to 4th October) formed over Bay of Bengal and Arabian Sea respectively the Arabian Sea, from 1st to 4th June. In addition to this one deep depression also formed during 12-15 September 2021.Apart from the above depicted intense Low pressure systems, there were 12 more systems of comparatively lesser intensity which manifested as Low Pressure Area / Well marked Low Pressure Area.

IMD adopted the new strategy is based on the existing statistical forecasting system and the newly developed Multi-Model Ensemble (MME) based forecasting system for 2021 Southwest monsoon season. The spatial tercile probability forecast for rainfall also issued based on MME. Addition to that monthly rainfall over the country as a whole for the months of June, July, August, September & second half of the season (Aug-Sept) were issued. IMD has also issued a separate forecast for the Monsoon Core Zone (MCZ) in addition to the four homogeneous regions. Most of the seasonal forecast issued during the 2021 monsoon season was correct and within the forecast limit. The spatial probability rainfall forecast also match well with the observed rainfall pattern.

The formation of five low pressure systems over the North Bay of Bengal and Arabian sea helps to get good amount of rainfall during the season especially in September month. The negative IOD condition over the Indian ocean is one of the major factors which cause large rainfall deficiency observed in August month. La Nina condition helps to get good amount of rainfall during end of monsoon season.

The present report spells out challenging aspects of monsoon monitoring, variability and prediction; and provides useful and authentic information about the 2021 southwest monsoon season for operational forecasters, researchers and other users. I sincerely appreciate all the authors and co-authors of the various chapters of the report for their valuable contribution. I also appreciate the efforts made by the Editors and officers/staff of the Climate research and Services, IMD, Pune in bringing out this Meteorological Monograph.

Monsoon 2021

A Report

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1

REGIONAL CHARACTERISTICS OF THE SOUTHWEST MONSOON-2021

Sunitha Devi S, K Sathi Devi, Rajendra Kumar Jenamani, Soma Senroy, Naresh Kumar, Anupam Kashyapi and S. D. Sanap

This chapter discusses the observed features of southwest monsoon 2021 covering various synoptic situations during the advance, mature and withdrawal phases.

1.1 Onset and Advance of Southwest Monsoon 2021

1.1.1 Arrival of Southwest Monsoon Current over the Andaman Sea

Strengthening of the southwesterly winds in the lower tropospheric levels with enhanced cyclonic shear vorticity resulted in consistent widespread convective activity over the southern parts of the Bay of Bengal and Andaman & Nicobar Islands during the third week of May. The resultant increase in rainfall indicated the arrival of the southwest monsoon over this region on 21stMay 2021. It further advanced into the entire Andaman Sea, Andaman & Nicobar Islands, some parts of Maldives-Comorin area, Southwest & East-central Bay of Bengal (BoB), most parts of Southeast BoB and some parts of West-Central BoB by 27th May.

1.1.2 Monsoon onset over Kerala

Southwest Monsoon (SWM) set in over Kerala on 03rd June, against the normal date of 01st June. It was declared based on the strengthening of the monsoonal flow, below the threshold value of Outgoing Longwave Radiation (OLR) and sustained increase in rainfall, the laid down criteria utilised for delaring the onset of SWM over Kerala (Fig.1).

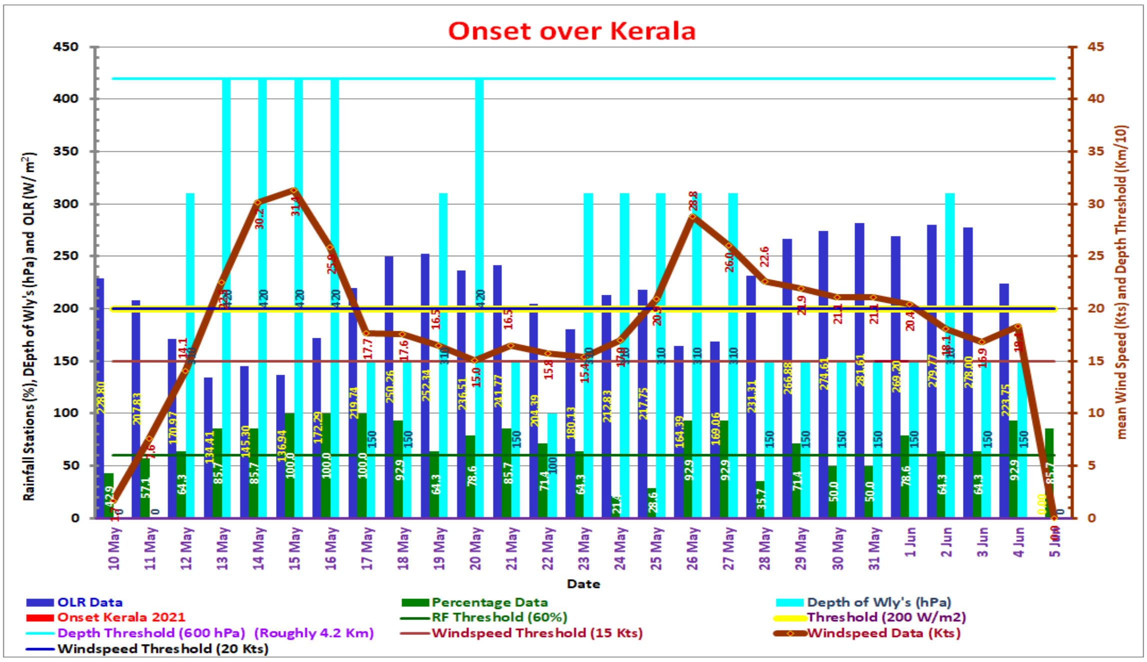

Fig 1.1: Time-series of percentage of the monitoring stations reporting rainfall more than 2.5 mm per day, INSAT derived OLR, depth of westerlies and wind speed at 925 hPa.

The average wind speed at 925 hPa over the region, 5-10°N and 70-80°E had been 16.9 knots. The INSAT-3D derived OLR value in the box confined by Lat. 5-10^{o}N, Long. 70-80^{o}E was 278 W/m^{2} and the percentage of the rainfall monitoring stations which reported more than 2.5 mm rainfall per day was 64.3 % on 3rd June as depicted in Fig. 1.1.

1.1.3 Advance of Southwest Monsoon

The isochrones of the advance of monsoon over the country are given Fig.1.2. The SWM advanced into some parts of the south Arabian Sea, Lakshadweep area, south Kerala, south Tamil Nadu, remaining parts of Comorin - Maldives area and some more parts of southwest BoB on 3rd June. It then rapidly advanced into entire central and some parts of north Arabian Sea, entire Konkan including Mumbai and most parts of interior Maharashtra, some parts of south Gujarat region, some more parts of Telangana and Andhra Pradesh, most parts of central BoB and some parts of North BoB on the 9th June.Further, it advanced over most of the central and parts of northern plains by 13th June.

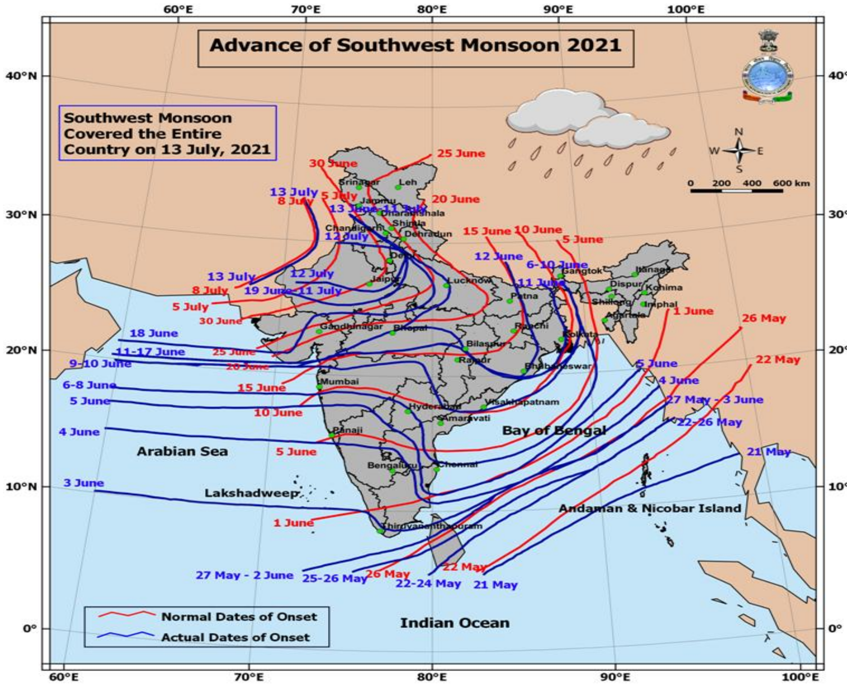

Fig.1.2: Isochrones of the advance of southwest monsoon 2021

Thereafter a hiatus occurred on the western part of the advance line due to the weakening of the monsoonal flow. It further advanced into the remaining parts of the north Arabian Sea, Saurashtra, Gujarat Region, Madhya Pradesh, entire Kutch, some more parts of Rajasthan and west Uttar Pradesh on 19th June. In association with the continued prevalence of moist easterly winds from the BoB in the lower tropospheric levels, enhanced cloud cover and scattered to fairly widespread rainfall activity, the SWM further advanced into most parts of Rajasthan, Punjab; some more parts of Haryana and West Uttar Pradesh on 12th July after a hiatus of about three weeks. It then covered the remaining parts of Punjab, Haryana and Rajasthan and thus the entire country on 13th July, against the normal date of 8th July.

1.2 Semi-Permanent Systems

1.2.1 Heat Low

The development of a Heat Low over the sub-continent and its location over central parts of Pakistan in July is a significant factor of the establishment of monsoon. The intensity of the heat low has been correlated with monsoon activity quite often (Ramage, 1971). The departure of pressure from normal in this region and gradient of departures are considered to be one of the deciding factors for monsoon activity. Below normal pressures in the Heat Low region and above normal pressures in the Peninsula are regarded as favouring monsoon activity over the country. The pressure gradient would then be strong over the Peninsula which is favourable to monsoon rains. The Heat Low may also strengthen when the ridge aloft weakens under the influence of westerly troughs moving further north.

The lowest and the second-lowest (month wise) values of the heat low were:

June: 992 hPa (on 11, 12,16)and 994 hPa (10, 13, 14)

July: 990 hPa (on 28) and 994 hPa (on 1,2,10,22,23,26,27,29)

Aug:998hPa (on 26) and 994 (03 Aug)

Sept: 1000 hPa (on 5,6,8,9,13) and 1002 hPa(on 2,3,4,7,10,11,12,14,16,17,22)

1.2.2 Monsoon Trough

During the SWM, a trough extends from the Heat Low over the Indo-Pakistan region, southeastwards to Gangetic West Bengal. On mean sea level charts, the trough line runs from Ganganagar to Kolkata through Allahabad, with westerly to south-westerly winds to south and easterlies/south-easterly to the north of the trough line. The location of the trough line fluctuates has an important role in deciding the monsoon activity and rainfall. The position of the trough line close to the foothills of the Himalayas is referred to as the 'break-in monsoon'. Rainfall activity over most regions of the country decreases during the break phase of the monsoon. However, foothills of the Himalayan mountain belt experiences heavy falls which causes occasional floods in the rivers originating over there. The trough occasionally shifts to the central parts when monsoon depressions from the North Bay move west/west northwest-wards across the country.

A trough at mean sea level made its first appearance in the first week of June with a location south of its normal position. It disappeared in the second week of June and reappeared at the south of its normal position during the third week. During the fourth week, it was north of its normal position for most of the days and near foothills for two days. It was found north of normal position on two days and near the foothills of the Himalayas for the remaining days in the first week of July.The monsoon trough was south of normal position for most of the days during the second week. In the third week, the western end of the monsoon trough was found southwest of its normal position on two days and at the normal position for the remaining days, while the eastern end was found northeast of its normal position throughout the week. It was found at its normal position on three days, its western end was found to the north of its normal position and the eastern end to the south of its normal position on the remaining days of the fourth week in July. The Monsoon trough was in a normal to near-normal position at the beginning of the first week of August and south of its normal position for the initial two days of the second week and remained at near normal positions on the rest of the days of the week. The monsoon trough was found north of its normal position/close to the foothills during most of the days in the third week of August. The position of the monsoon trough was mostly south of its normal position during the first and second week of September. The monsoon trough was found south of its normal position on three days and its western end was found south of its normal position & eastern end in the normal position on the remaining days of the third week of September. Subsequently it shifted to the south and gradually became disorganised in the 4^{th} week of September.

1.2.3 Tibetan Anticyclone

The high over Tibet known as the Tibetan Anticyclone (TA), from 500 hPa and above levels is a semi-permanent warm anticyclone. The position of the Tibetan high / TA is situated at about 25°N at 300 and 200 hPa and near 30°N at 100hPa over the southern periphery of Tibet. It is found to be more intense and a little north by its position in August. Climatologically the anticyclonic belt is found to be near about 26°N up to 200 hPa and 30°N at 100 hPa. Well distributed rainfall over Indian region is associated with the well pronounced and east-west oriented anticyclone over the Tibetan region at 500 and 300 hPa and high index circulation over Siberia, Mongolia and north China. During the first (second) week of June, TA was southeast (east) of its normal position. It was northeast of its normal position in the third and fourth week of June. The TA was mainly west of its normal position during the first week of July. It moved northeast of its normal position on the initial three days of the second week and west of its normal position on the remaining days of the week. In the third week, it shifted back to the northeast of its normal position for three days, moved west of normal position on two days and remained at normal position on remaining days of the week. In the last week of July, the TA was found to the southeast of normal position on two days, east of its normal position on two days, west of its normal position and at near normal position on one day each. The TA was normal for a few days and south of its normal position during most of the days in the first two weeks of August. During the third (fourth) week of August, it was east (west) of its normal position. In the month of September, the TA was found at the east of its normal position in the first week while it was mainly west/southwest of its normal position during the second week. During the third (fourth) week, it was mainly at the south-southeast(south-southwest) of its normal position.

1.2.4 Tropical Easterly Jet

Tropical Easterly Jet (TEJ) is an important component of the SWM circulation which can be seen in the upper-tropospheric levels (100-150 hPa) centred near about the latitude of Chennai (Krishnamurti and Bhalme, 1976). The jet stream runs from the east coast of Vietnam to the west coast of Africa. It exhibits periodic movements to the north and south of its normal location during the SWM season. Normally, the jet is at an accelerating stage from the South China Sea to South India and decelerates thereafter. Consequent upper-level divergence is regarded as favourable for convection upstream of 70^{o}E and subsidence downstream. This year,the TEJ got established over the southern tip of Peninsular India in the first week of June and the highest wind speed of 84 knots was recorded over Karaikal on 8^{th} June at 112 hPa.The highest wind speed of 126 knots was recorded at Chennai station on 2^{nd} August at 166 hPa followed by 125 knots by Kochi station on 15 August 2021 at 115 hPa. Apart from Chennai and Kochi, other stations reporting the jet wind speed were Thiruvanthapuram, Machlipatnam, Panjim and Mangaluru.

1.2.5 Mascarene High

The onset of monsoon is associated with a sudden acceleration of winds from the southern hemisphere towards India, across the equator. The southern hemispheric circulation regime along the Indian Ocean longitudinal belt is dominated by an anticyclonic circulation, around a region of high pressure centred at 30^{O}S/ 50^{O}E, known as Mascarene High (MH), off the coast of Madagascar. Sikka and Gray (1981) suggested that the MH undergoes short period intensity fluctuations due to the passage of extratropical waves of the southern hemisphere. The intensification of

MH strengthens the cross-equatorial flow in the form of Low-Level Jet and the corresponding monsoon current over the Arabian Sea. Normal pressure, actual pressure and departure from normal for the normal position of MH (centred at 30°S/ 50°E) during June to September 2021 is shown in Table 1.The MH with its mean position at 32.4º S/55.8^o E was stronger than normal by 2.3 hPa during the monsoon period June to September 2021. It was above normal during all the four months as shown in Table 1.1.

Month	*Normal Pressure (hPa)(approx.)	Actual Pressure (hPa)	Departure from normal hPa(approx)
June	1023.0	1027.5	+4.5
July	1025.5	1026.8	+1.3
August	1026.0	1026.8	+0.8
September	1023.5	1026.3	+2.8

Table 1.1: Month-wise and southwest monsoon season averaged values of Mascarene High and their departures

1.2.6 Somali Low-Level Jet

The lower tropospheric monsoon flow is essentially concentrated near the coast of East Africa in the form of a Low-Level Jet (LLJ). Fluctuations in the intensity of this LLJ takes place in association with the passage of extra-tropical westerly waves of the southern hemisphere. Strengthening of the LLJ is associated with increased monsoon activity along the west coast of India. For monitoring the monsoon low-level westerly flow, the Somali jet index is derived by Boos and Emanuel (2009). It is the square root of twice the domain mean kinetic energy of the 850 hPa horizontal wind in the region (50^{o}E - 70^{o}E, 5^{o}S – 20^{o}N). They utilized the NCEP operational analyses for the current year and NCEP reanalysis data for the climatology. Fluctuations in the Somali jet speed with the strengthening of the flow was observed in mid-July as well as in September (Figure 1.3).

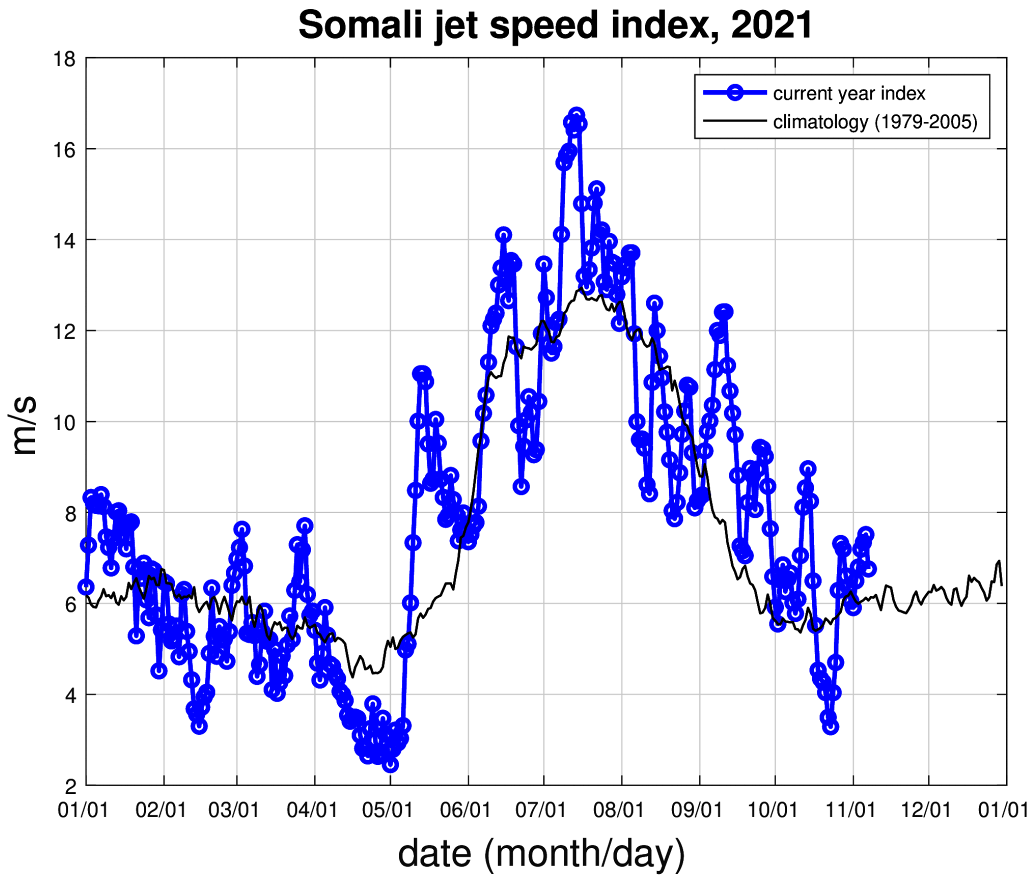

Fig.1.3: Somali jet-speed index for SWM 2021

1.3. Other Features:

1.3.1 Off-shore Trough

An extended offshore trough along the west coast of India with varying intensity and region of its presence was seen for the period 09-22nd June, 14-29th July, 19-21st Aug and 26-30th Aug 2021.

1.3.2 Intensity of Australian High (normally centred at 30^{o} S/140^{o}E)

The Australian HIGH centred at 31.8 ^{o} S / 136.4 ^{o} E was stronger than normal by an average of about 6.2 hPa during the entire monsoon period June to September 2021. Also it was above normal all through the four months of the season as shown in Table 1.2.

Month	*Normal Pressure (hPa) (Approx.)	Actual Pressure (hPa)	Departure from normal hPa (Approx)
June	1022.0	1028.4	+6.4
July	1022.0	1025.1	+3.1
August	1020.5	1028.0	+7.5
September	1018.0	1027.9	+9.9

Table 1.2: Intensity of Australian High during June to September 2021

1.3.3 Sub-Tropical Westerly Jet

Sub-Tropical Westerly Jet (STWJ) started shifting northwards from the second week of June. The highest wind speed of 70 knots was recorded over Kolkata on 18th June at 126 hPa. Subsequently, the STWJ shifted to the north of the Himalayas.

1.4 Synoptic Disturbances during SWM 2021

1.4.1Storms and Depressions

Climatologically about 6 monsoon depressions form over the North Indian Ocean during SWM season with a standard deviation of about 2.5. On an average about 2 systems each form during July and August and one each during June and September. This year there were 3 systems, one Deep Depression and 2 Cyclonic Storms, all of them forming in the month of September.The tracks of these systems areare given in Fig. 1.4

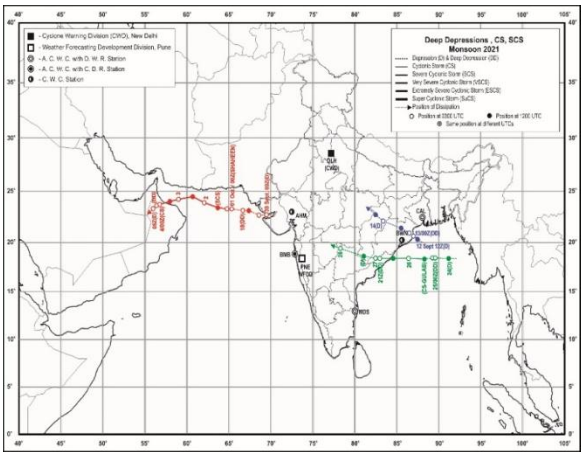

Fig.1.4: Tracks of deep depression and cyclones during SWM 2021.

1.4.1.1 Deep Depression over the BoB(12^{th}September – 15^{th}September 2021)

Under the influence of a cyclonic circulation over east-central BoB and neighbourhood,a low pressure area (LPA) formed over eastcentral and adjoining northeast BoB in the early morning (0530 hrs IST) of 11^{th} September, 2021. It lay as a Well MarkedLow pressure area (WML) over northwest and adjoining westcentralBoB in the early morning of 12^{th}. It concentrated into a Depression over northwest BoB and adjoining Odisha coast in the evening (1730 hrs IST) of 12^{th}. Moving west-northwestwards, it intensified into a deep depression over northwest BoB very close to Odisha coast in the early morning of $13^{th}$and crossed north Odisha coast, close to south of Chandbali between 0530 & 0630 hrs IST as a deep depression with maximum sustained wind speed of 30 knots (50-60 kmph). Continuing to move further west-northwestwards, it weakened into a depression over north Chhattisgarh & adjoining north interior Odisha in the morning (0830 hrs IST) of $14^{th}$and into a WML over northeast Madhya Pradesh &neighbourhood in the early morning of 15^{th}.

It caused active to vigorous monsoon conditions leading to extremely heavy rainfall at a few places over Odisha on 12^{th}& 13^{th}, at isolated places over Chhattisgarh on 13^{th} and over East Madhya Pradesh on 14^{th}. In conjunction with another low pressure area over Gujarat, extremely heavy rainfall at a few places also occurred over Saurashtra and north Konkan on 13^{th} September. Low level convergence of wind & enhanced moisture incursion from the BoB in association with a trough extended eastwards across the system also caused extremely heavy rains at isolated places over West Bengal on 14^{th} September.

1.4.1.2 Cyclonic Storm Gulabover the BoB(24-28 September)

Under the influence of a cyclonic circulation over east-central BoB& neighbourhood, a low pressure area formed over the same region in the morning (0830 hours IST) of 24^{th} September. It lay as a well marked low pressure area in the same afternoon (1430 hours IST) over eastcentral and adjoining northeast BoB. It concentrated into a depression over eastcentral and adjoining northeast BoB in the same evening (1730 hours IST) of 24^{th} September. Moving west-northwestwards, it further intensified into a deep depression over north & adjoining central BoB in the early morning (0530 hours IST) of 25thSeptember. Continuing to move further west-northwestwards, it intensified into the cyclonic storm **“GULAB”** over northwest and adjoining westcentralBoB in the same evening of 25th September, 2021. Thereafter, it intensified gradually and reached it’speak intensity of 75-85 kmph gusting to 95 kmph around noon (1130 hours IST) of 26th September. Continuing to move further westwards, it crossed North Andhra Pradesh and adjoining south Odisha coasts near 18.4°N/84.2°E (20 km north of Kalingapatnam) with maximum sustained wind speed of 75-85 gusting to 95 kmph during 1930-2030 IST of 26th September. Thereafter, it weakened into a deep depression in the early hours (0230 hours IST) of 27th September over north Andhra Pradesh and adjoining south Odisha, into a depression over south Chhattisgarh in the evening (1730 hours IST) and into a WML over western parts of Vidarbha&neigbourhoodaround noon of 28th September 2021.

It also caused active to vigorous monsoon conditions leading to heavy to very heavy rainfall at many places with extremely heavy rainfall at a few places over costal Andhra Pradesh &Yanam and heavy to very heavy rainfall over Odisha on 26th. On 27th, it caused extremely heavy rainfall at isolated places and heavy to very heavy falls at many places over Telangana and heavy to very heavy rainfall at isolated places over Odisha, Chattisgarh, coastal Andhra Pradesh &Yanam, Marathwada, Vidarbha, West Madhya Pradesh and Gujarat region. On 28th, it caused heavy to very heavy rainfall over West Madhya Pradesh, Marathwada, Madhya Maharashtra, Saurashtra & Kutch and heavy to very heavy rainfall at many places with extremely heavy rainfall at isolated places over Gujarat region.

1.4.1.3 Severe cyclonic storm Shaheen over the Arabian Sea (30th September- 4th October)

The remnant of cyclonic storm Gulab emerged as a WML into south Gujarat region & adjoining Gulf of Khambhat in the morning (0830 hours IST) of 29th September. It concentrated into a depression over northeast Arabian Sea (AS) & adjoining Kutch, in the early morning (0530 hours IST) of 30th September. Moving west-northwestwards, it further intensified into a deep depression over the same region in the midnight (2330 hours IST) of 30th September.Thereafter it moved westwards and intensified into cyclonic storm “Shaheen” over the northeast AS off Gujarat coast in the early morning of 1st October, 2021.Moving westwards for some time, it moved west-northwestwards and intensified into a severe cyclonic storm in the evening (1730 hours IST) of 1st October over northwest & adjoining northeast AS.Continuing to move further west-northwestwards till evening of 2nd October, it re-curved west-southwestwards and crossed Oman coast during 0030-0130 IST of 4th Oct. with wind speed of 95-105 gusting to 115 kmph. Thereafter moving west-southwestwards, it weakened into a cyclonic storm over North Oman and adjoining United Arab Emirates in the early morning (0530 hours IST), into deep depression in the morning (0830 hours IST), into a depression around noon (1130 hours IST) and into a WML in the evening (1730 hours IST) of 4th October over the same region.

Since the system moved away from the Indian coast, it did not cause any severe weather over the Indian mainland.

1.4.2 Low-Pressure Areas/Well Marked Low-Pressure Areas

Apart from the above depicted intense Low pressure systems, there were 12 more systems ofcomparatively lesser intensity which manifested as Low Pressre Area / Well marked Low Pressure Area at mean Sea level pressure field.The approximate track followed by these are shown in Fig. 1.5. They are briefly discussed in the following sub-sections.

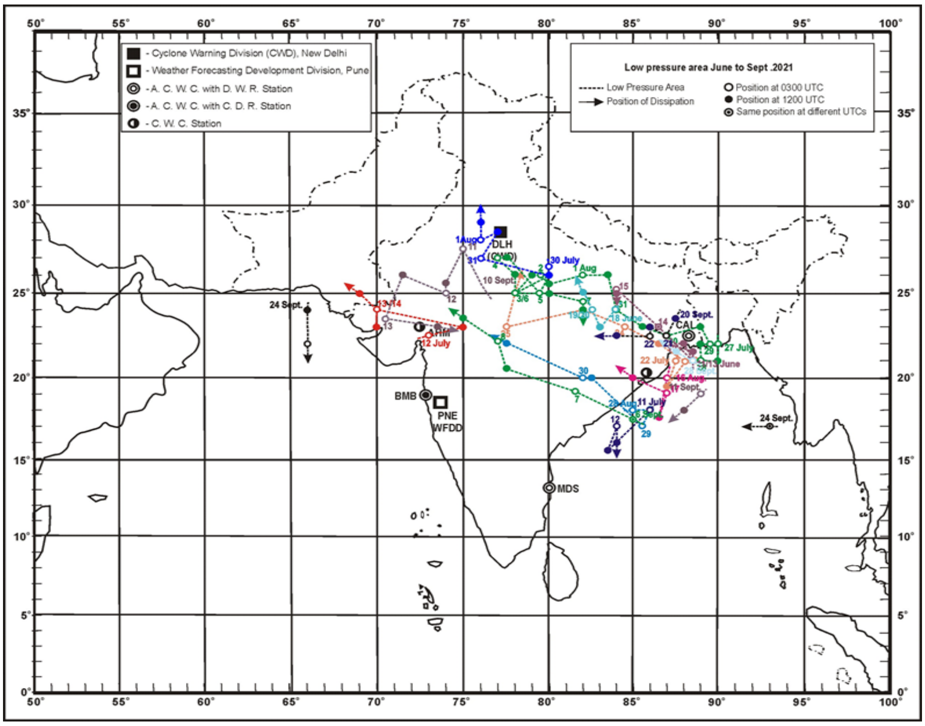

Fig.1.5: Tracks of low / well marked low pressure areas during SWM 2021.

1.4.2.1 Low-pressure area over northwest Bay of Bengal (11-15 June 2021)

Under the influence of a cyclonic circulation over northwest BoB, a low-pressure area formed over northwest BoB and adjoining coastal areas of Odisha and West Bengal on 11th morning. It lay over northwest BoB, adjoining coastal areas of West Bengal and north Odisha with the associated cyclonic circulation extending up to mid-tropospheric levels tilting southwestward with height on 12th& 13th. It lay over south Jharkhand and neighbourhood on 14th, over east Uttar Pradesh and adjoining Bihar on 15th and became less marked on 16th.

1.4.2.2 Low-pressure area over South Gujarat and adjoining northeast Arabian Sea (12-15 July)

A low-pressure area formed over south Gujarat and the adjoining northeast Arabian Sea with the associated cyclonic circulation extending up to mid-tropospheric levels on the 12th. It lay over the Saurashtra coast and neighbourhood on 13th, over coastal areas of Kutch and neighbourhood on 14th and became less marked on 15th morning.

1.4.2.3 Low-pressure area over west-central and adjoining northwest Bay of Bengal (11-13 July)

Under the influence of a cyclonic circulation over coastal Odisha and neighbourhood, a low-pressure area formed over west-central and adjoining northwest Bay of Bengal off north Andhra Pradesh &south Odisha coasts on 11th. It persisted over the same region on12th and became less marked on13th.

1.4.2.4 Well Marked Low-pressure area over northwest Bay of Bengal (22-26 July)

Under the influence of a cyclonic circulation over northwest BoB and neighbourhood, a low-pressure area formed over the same region on 22nd morning. It then persisted over the same region with the associated cyclonic circulation extending up to 7.6 km above m. s. l. tilting southwestward with height on 22nd. It lay as a WML over northwest BoB off north Odisha-West Bengal coasts on 23rd. It lay over Jharkhand and adjoining areas of north Chhattisgarh, Odisha on 24thmorning and then lay as a low-pressure area over Jharkhand, adjoining north Chhattisgarh in the same evening. It lay over northern parts of central Madhya Pradesh and neighbourhood on 25th, over northwest Madhya Pradesh and neighbourhood on 26thmorning and then became less marked in the evening.

1.4.2.5 Well marked Low-pressure Area over North BoB (27 July- 08 August)

Under the influence of a cyclonic circulation over north BoB and neighbourhood, a low-pressure area formed over the same region on the 27th morning. It lay as a WML over south Bangladesh, adjoining north BoB and West Bengal on 28thmorning, over interior parts of Gangetic West Bengal and neighbourhood on30th morning, over northwest Jharkhand and adjoining Bihar on 31st July morning, over southeast Uttar Pradesh and neighbourhood 31stJuly evening and persisted over the same region on 1stAugust. It lay over southern parts of central Uttar Pradesh and neighbourhood on 1stAugust evening, over southeastern parts of west Uttar Pradesh and neighbourhood on 2ndmorning and over northwest Madhya Pradesh and neighbourhood on 3rd morning. It lay as a low-pressure area over the same region on the 4th& 5th August. Further it gradually drifted east-northeastwards and became less marked on 8th August.

1.4.2.6 Low-pressure area over southern parts of central Uttar Pradesh (30 July- 2nd August)

A low-pressure area formed over southern parts of central Uttar Pradesh with the associated cyclonic circulation extending up to 7.6 km above m. s. l. on 30th July.

It lay over southwest Uttar Pradesh and neighbourhood on 31stJuly, persisted there on 1st Augustand became less marked on 2nd August.

1.4.2.7 Low-pressure Area over west-central and adjoining northwestBoB (16-18 August)

Under the influence of a cyclonic circulation over west-central and adjoiningnorthwest BoB off north Andhra Pradesh- south Odisha coasts, a low-pressure area formed over the same region in the afternoon of 16th.It lay over coastal Odisha and adjoining the northwest BoB on 17th and became less marked on 18th.

1.4.2.8 Low-pressure area over northwest & adjoining west-central BoB off north Andhra Pradesh – south Odisha coasts (27-31 August)

Under the influence of a cyclonic circulation over northwest BoB off West Bengal coast, a low-pressure area formed over northwest and adjoining the west-central BoB off north Andhra Pradesh - south Odisha coasts with the associated cyclonic circulation extending up to 5.8 km above m. s. l.tilting southwestward with height on 28th . It persisted there on 29th and lay over south Chhattisgarh and neighbourhood on 30th morning. It lay over western parts of Vidarbha and neighbourhood on 31stAugust morning and became less marked subsequently.

1.4.2.9 Well marked Low-pressure area northwest and adjoining the west-central BoB off south Odisha-north Andhra Pradesh coasts(6-9 September)

Under the influence of a cyclonic circulation over north and adjoining east-central BoB, a low-pressure area formed over northwest and adjoining west-central BoB off south Odisha-north Andhra Pradesh coasts with the associated cyclonic circulation extending up to 7.6 km above m. s. l., tilting southwestward with height on 6th. It lay as a WML overwest-central and adjoining northwest BoB and north Andhra Pradesh - south Odisha coasts on the 6th evening. It lay over north coastal Andhra

Pradesh and adjoining south Odisha and neighbourhood on 7th morning and over south Chhattisgarh and neighbourhood at 1430 hrs IST of 7th. It lay over southeast Madhya Pradesh and adjoining parts of north Vidarbha on 7th evening. It weakened into a low-pressure area and layover southwest Madhya Pradesh and neighbourhood on 8th and became less marked on 9th morning.

1.4.2.10 Well marked Low-pressure area over northwest BoB and adjoining coastal areas of West Bengal (28-30 September)

Under the influence of a cyclonic circulation over northeast adjoining east-central BoB, a low-pressure area formed over northwest BoB and adjoining coastal areas of West Bengal in the forenoon of 28th.It lay as a WML over the same region in the afternoon of the same day.It then lay over western parts of Gangetic West Bengal and adjoining Jharkhand on29th,over northwest Jharkhand and neighbourhood on 30thSeptember morning and became less marked subsequently.

1.4.2.11 Low Pressure Area over east Rajasthan and neighbourhood (10-13 September)

Under the influence of a remnant cyclonic circulation of a previous Low Pressure area over central parts of west Madhya Pradesh & adjoining east Rajasthan,a low-pressure area formed over east Rajasthan and neighbourhood on 10th which persisted over the same region on 11th.Moving southwestwards, it lay over southwest Rajasthan and adjoining Gujarat Region on 12th, over south Gujarat region and neighbourhood on 13th morning and became less marked in the evening.

1.4.2.12 Low Pressure Area overNE Arabian Seaand adjoining coastal areas of Pakistan (24-26 September)

Under the influence of a cyclonic circulation over Saurashtra & neighbourhood, a low-pressure area formed over northeast Arabian Sea and adjoining coastal areas of Pakistan with the associated cyclonic circulation extending up to mid-tropospheric levels in the evening of 24th. It lay over northeast Arabian Sea on 25th and became less marked in the morning of 26th.

1.4.3 Upper Air Cyclonic Circulations

There were 119 upper air cyclonic circulations (in lower, middle and upper tropospheric levels) during the season. The month-wise break-up of these is: 46, 34, 21 & 18 during June, July, August and September respectively.

1.4.4 Eastward Moving Cyclonic Circulations/Western Disturbances

There were 22 eastward-moving systems as upper air cyclonic circulations. The month-wise distribution of these is: 7, 4, 7 & 4 during June, July, August and September respectively.

1.5 Significant weather events during the season

The significant weather events which affected normal life and damage to property, excluding those from the lack of timely rains, are depicted in Fig. 1.6. High impact weather manifested as extremely heavy rainfall (rainfall amount ≥ 25cm during 24 hours) is also marked over the affected sub-divisions and representative amounts with their location and dates of occurrence are given in the Table along with the figure. A detailed analysis of some of these events is made in the subsequent chapters.

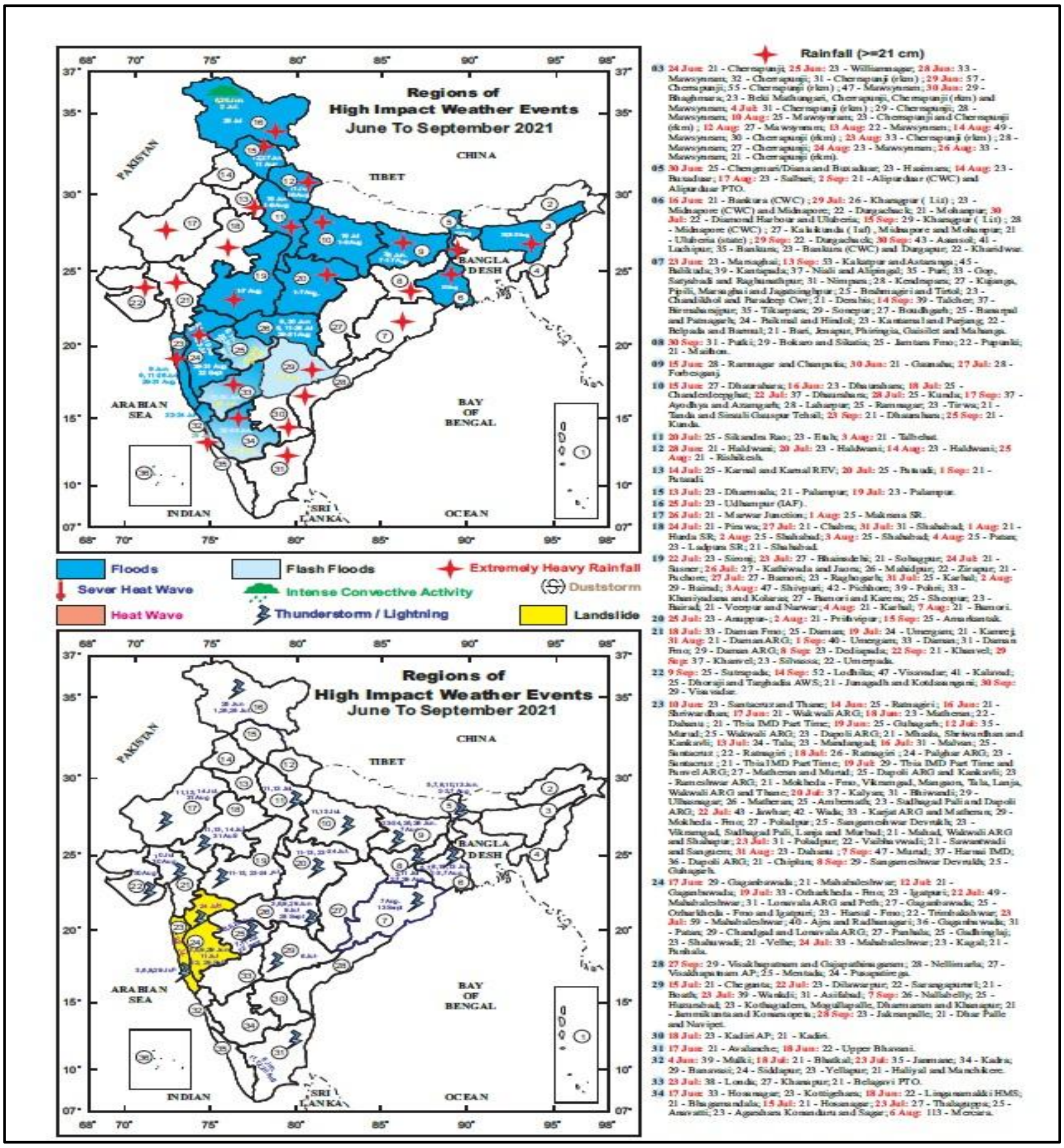

Fig.1.6: High Impact Weather Events pertaining to events & dates as per legends

1.6 Low-pressure Systems over Other Oceanic Areas during June to September 2021.

1.6.1 Low-pressure Systems over West Pacific Ocean/ South China Sea

There were17 low-pressure systems (reaching the intensity of Tropical depression and above) in the northwest Pacific Ocean / South China Sea during June – September 2021. The month-wise break-up is given below:

Low-Pressure Systems	June	July	August	September	TOTAL
Tropical Depression (T.D.)	01	02	01	01	04
Tropical Storm (T.S.)	02	02	04	01	10
Typhoon/Super Typhoon	00	01	00	02	02
TOTAL	03	05	05	04	17

1.6.2 Low-pressure Systems over South Indian Ocean

No low-pressure system (TD, TS or Typhoon) was reported in Southern Hemisphere during June- September 2021.

1.6.3 Troughs in the Mid Latitude Westerlies from Northern & Southern Hemispheres Affecting the Indian Monsoon

(i) Troughs in Mid &Upper tropospheric Westerly Winds from Northern Hemisphere

The number of troughs in westerlies which moved across Indian region from west to east penetrated to the south of 30^{o} N during each month of the season was as follows:

Atmospheric Level	June	July	August	September	Total
500 hPa	06	02	02	04	12
300 hPa	04	03	04	04	15

(ii) Upper-Air Troughs in westerlies over the South Indian Ocean, which penetrated to the north of latitude 30^{0}S.

The troughs in upper air westerlies which moved across the South Indian Ocean from west to east& penetrated to the north of Lat.30^{0} S, in the Southern Hemisphere, month-wise from June to September 2021 was as follows.

Atmospheric Level	June	July	August	September	Total
500 hPa	04	04	05	04	17
300 hPa	05	06	05	04	20

1.7 Withdrawal of the Southwest Monsoon

The isochrones of withdrawal of monsoon are given in Fig.1.7.Due to the formation of the Deep Depressionand cyclonic storm,*'Gulab'* over the BoB andits movement, widespread rainfall was reported over the central, northern&Northwest Indian region, which delayed the monsoon withdrawal process from Northwest India. With the establishment of an anticyclonic circulation in the lower tropospheric levels over western parts of northwest India and substantial reduction in the moisture content & rainfall, the withdrawal of SWM 2021 commenced on 06th October against the normal date of 17th September.Accordingly, the SWM withdrew from some parts of West Rajasthan and adjoining Gujarat and the withdrawal line passed through 28.5°N / Long. 72.5°E, Bikaner, Jodhpur, Jalore, Bhuj and Lat. 23°N / Long. 68°E on 6th October.Further withdrawal was rapid upto 11th October when the withdrawal line passed through Lat. 27.0°N / Long. 92.0°E, Kohima, Silchar, Krishnanagar, Baripada, Malkangiri, Hanamkonda, Aurangabad, Silvasa, Lat. 20.0°N / Long. 65.0°E and Lat. 20.0°N / Long. 60.0°E.Subsequently, owing to the formation of the low-pressure area over West-centralBoB and associated rainfall activity, the withdrawal process got stagnated in thesecond week of October. SWMwithdrew from the entire country on 25th October against the normal date of 15th October. Simultaneous with this withdrawal, the northeast monsoon rains also commenced over southern parts of peninsular India from 25th October 2021.

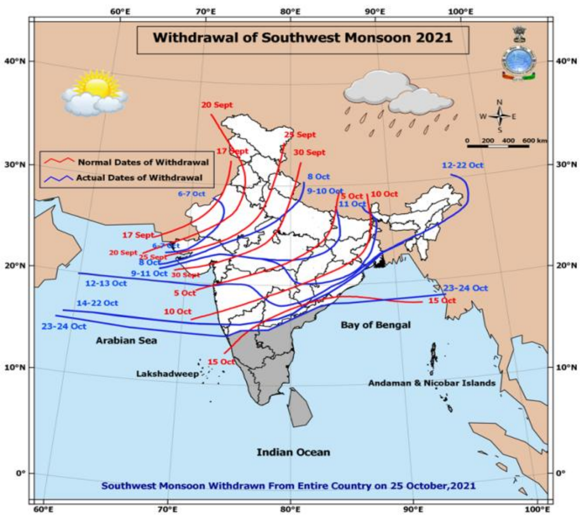

Fig.1.7: Isochrones of withdrawal of South West Monsoon 2021

1.8 Concluding remarks

Barring a large temporal & spatial variability, the all IndiaSummar monsoon rainfall for the year 2021 was 99 % of its long period average (87.0 cm against long period average of 88.0 cm based on data of 1961-2010).

i) Southwest monsoon advanced overAndaman Seas during the last week of May and the onset of monsoon over Kerala took place on 3rd June against the normal date of 1stJune.It covered the entire country on 13th July, with a delay of 5 days.

ii) The season witnessed the formation of a Deep Depression & the Cyclonic Storm 'Gulab' over the Bay of Bengal as well as the remnant of Gulab intensifying into Severe Cyclonic Storm 'Shaheen' over the Arabian Sea, all of which occurring in the month of September.

iii) Though there was no monsoon depression during June, July &August, there were in all 12 Low Pressure areas & well marked Low pressure areas altogether during the season, out of which 1 formed in June, 5 in July, 2 in August and 4 in September.

iv) The convectively supressed atmospheric general circulation regime had an adverse impact on the maintenance of the monsoon trough over the Indian region during the month of August. This inturn manifested in the lesser number of monsoon Lows resulting in subdued rainfall as well.

v) Withdrawal of southwest monsoon from northwest Indian region as well as from entire country was delayed due to the formation of the synoptic systems over BoB and its northwest/westward movement. It withdrew from the entire country on 25th October with a dealy of about 10 days.

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2

GLOBAL AND REGIONAL CIRCULATION ANOMALIES

Arti B. Bandgar, O. P. Sreejith, Satyaban B. Ratna, Saber Aliand & D. S. Pai

In this Chapter, main features of global climate anomalies like sea surface temperature, outgoing long wave radiation and circulation features during 2021 southwest monsoon season are discussed and important factors responsible for the observed rainfall patterns over India during the season are identified.

2.1 Sea Surface Temperature (SST) Anomalies

2.1.1 Equatorial Pacific Ocean

Evolution of SST anomalies in the four Nino regions since November 2020 to October 2021 is shown in the Fig. 2.1. La Niña conditions as per the Nino 3.4 index, were observed during later part of 2020, which were slowly started weakening in subsequent months. However, La Niña conditions prevailedtill the month of April 2021. During May 2021, La Niña conditions were turned into ENSO neutral conditions. Though ENSO neutral conditions continued in the following months, cooling trend of Nino 3.4 SST anomalies was continued and again turned into La Niña conditions in the month of August 2021. The strength ofLa Niña conditions were further increased during the latter months of September and October 2021.

Nino3.4 average SST anomaly index in November 2020 was -1.35°C and it was -0.61°C in the month of April 2021.During May and June, it was -0.33°C and -0.14°C respectively which was well within the neutral ENSO range. Again from July, Nino 3.4 index showed increased cooling and by end of August it reached to -0.48°C, which was just closeto the La Niña threshold. Thus La Niña has started developing during the month of August 2021. In September 2021, La Niña was established with the Nino 3.4 SST anomaly value -0.57°C which further reached to -

0.9°C by end of the October 2021. Therefore, during most time of the year 2021, the Nino 3.4 SST anomaly was remained to the cooler side of normal SSTs.

By and large, during first half of the monsoon season, neutral ENSO conditions were prevailing over the Pacific. Whereas, (weak) La Niña conditions prevailed during second half of the monsoon season 2021. The evolution of SST anomalies in the Nino3 and Nino4 regions was nearly similar to Nino3.4regions. Similar to the other Nino regions, the Niño1+2 SST anomalies were negativetill the end of monsoon season.

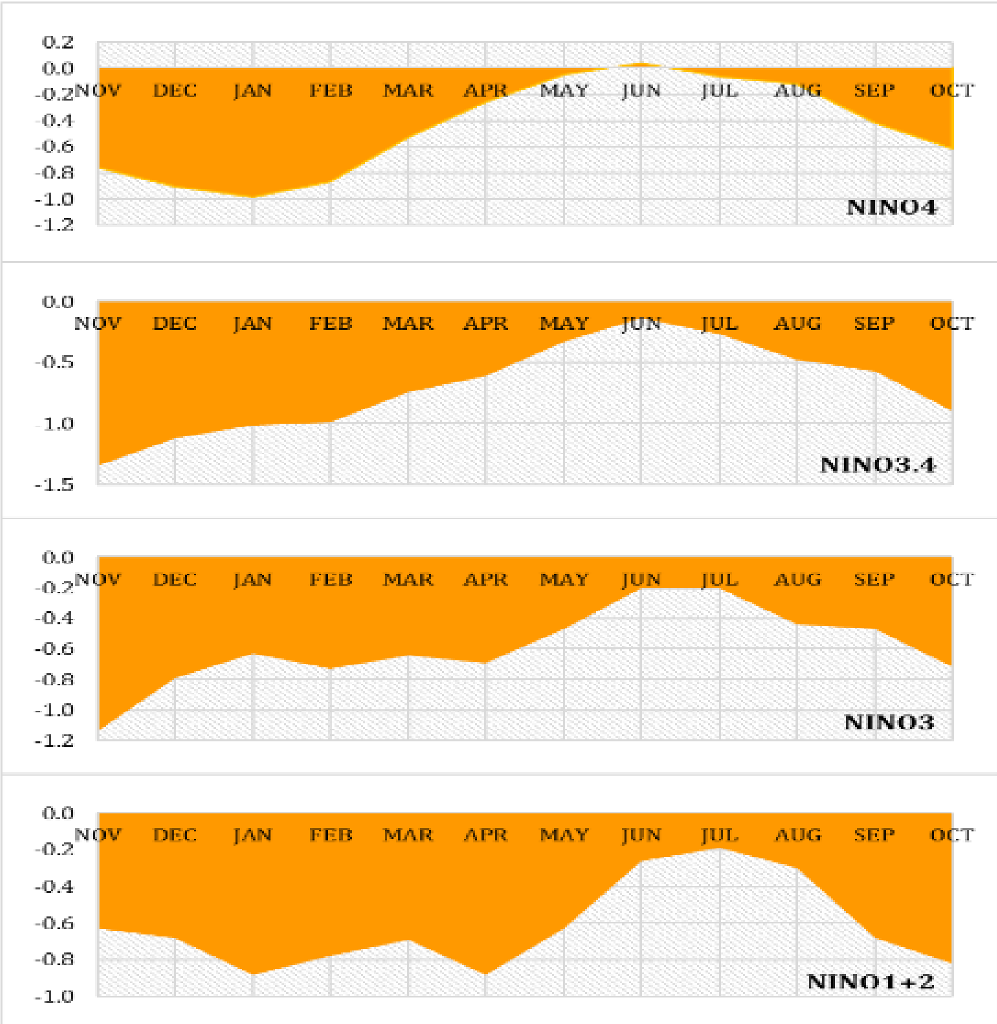

Fig. 2.1 Time series of area-averaged sea surface temperature (SST) anomalies (°C) in the Niño regions [Niño-1+2 (0°-10°S, 90°W-80°W), Niño-3 (5°N-5°S, 150°W-90°W), Niño-3.4 (5°N-5°S, 170°W-120°W), Niño-4 (150ºW-160ºE and 5ºN-5ºS)]. (Data Source: ERSSTv5, NOAA).

Spatial pattern of monthly SST anomalies for the period May to September 2021 is shown in Fig.2.2. As seen in Fig.2.2, during most of the months, positive SST anomalies were observed over western parts of the Pacific Ocean especially over west equatorial and north Pacific Ocean and negative SST anomalies were observed over eastern equatorial Pacific and southeast equatorial Pacific. During month of May, normal to warmer than normal SST anomalies were observed in the western equatorial Pacific and cooler than normal SST anomalies were observed over central and eastern equatorial Pacific Ocean. Then there was decreasingstrength in the cooling of SST anomalies over central and eastern Pacific as La Niña conditions turned into neutral ENSO conditions which was seen in spatial patterns during June and July 2021. However, July onwards Warmer than normal SSTs were started developing over extreme eastern parts of equatorial Pacific and such warming was observed in many pockets of the region. However, there was againincrease in cooler SSTs over some parts of eastern equatorial Pacific during subsequent months from August to September and spread of cool SSTs was also increased. By the end of September, warmer SSTs over the central equatorial Pacific have shifted over western parts of equatorial Pacific Ocean. In addition to this, there were positive SST anomalies were observed over the north Pacific Ocean during most of the months from May to September except some isolated region over extreme north.

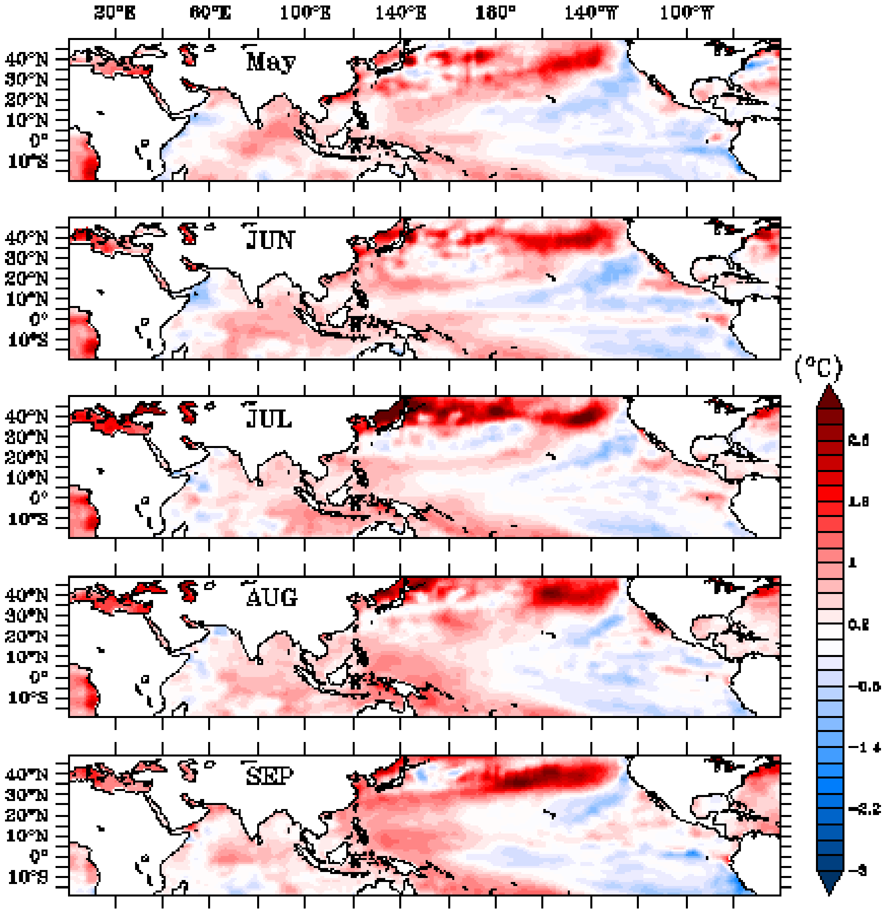

Fig.2.2Global Monthly SST anomalies for May to September 2022. (Data Source: ERSSTv5, NOAA)

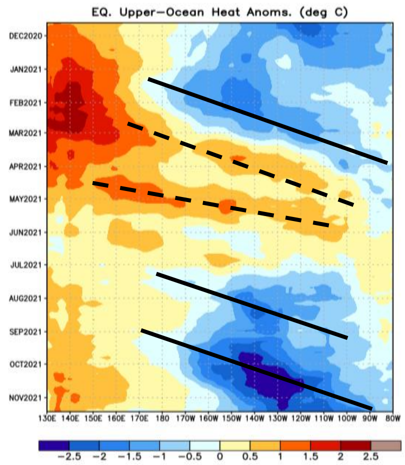

Fig.2.3 The equatorial upper-ocean heat anomalies (^{o}C) over equatorial Pacific. (Source: Climate Prediction Centre)

These features are also seen in the Hovmöller diagram (time Vs longitude) of equatorial heat content anomalies as shown in Fig.2.3. It is seen that upper ocean of equatorial Pacific was warmer than normal especially in the western and central side since December 2020 to May 2021. While, cooler than SSTs from central to east equatorial Pacific Ocean was observed during the period.Thereafter, during June and July warmer heat anomalies have reached up to extreme east in the upper (0-300m) of tropical Pacific. From the month of July again, negative heat content started building up in the east and started further spreading. The decrease in the oceanic heat anomalies across the equatorial Pacific is caused by the eastward propagation of upwelling Kelvin wave. The warm (down-welling) phase is indicated by dashedlines and cool (up-welling) phase indicate by solid line. The down-welling and warming occur in the leading portion of a Kelvin wave, and up-welling and cooling occur in the trailing portion. There were three up-welling phases of a Kelvin wave propagation events observed during January 2020 to November 2021.First one in January to end of April, second one from Julyto August and even continued further. With the passage of an upwelling equatorial oceanic Kelvin wave in September 2020, below average subsurface temperatures extended across much of the equatorial Pacific. Also, there were two down-welling phases of an equatorial oceanic Kelvin wave observed during February 2020 to May 2021.

2.1.2 Indian Ocean

It is seen in the Fig.2.2 that in the month of May positive SST anomalies have observed over Arabian Sea and Bay of Bengal. From June, area of strength of warmer than normal SST anomalies has started decreasing over northern most parts of Arabian Sea. It kept decreasing till end of the monsoon season. In the Bay of Bengal also spread of warmer than normal SST anomalies has decreased by the end of monsoon season. In the month of May warmer SST anomalies have observed over most parts of Indian Ocean, however, western equatorial Indian Ocean was slightly cooler than eastern equatorial Indian Ocean with weak positive Indian Ocean dipole (IOD) conditions during May and in subsequent months of June, July and August. However, in the month of September spatial pattern of weak negative IOD has weakened with slightly warmer SST anomalies over both the west and east Indian Ocean.

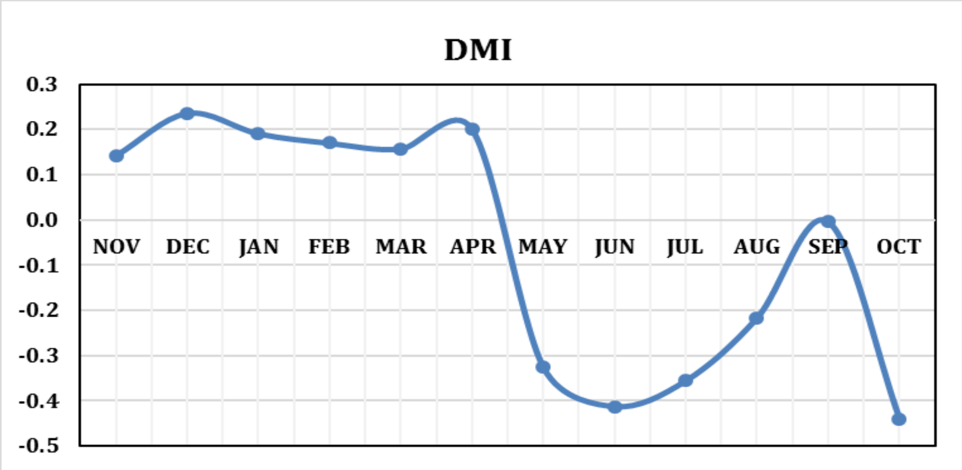

Fig. 2.4 The time series of Dipole Mode Index (DMI) representing Indian Ocean Dipole Condition (Source: https://stateoftheocean.osmc.noaa.gov/sur/ind/dmi.php) from November 2020 to October 2021.

The Fig.2.4 shows the time series of Dipole Mode Index (DMI) for the period November 2020 to October 2021. The DMI represents the intensity of the IOD defined as the anomalous SST gradient between the western equatorial Indian Ocean (50^oE-70^oE and 10^oS-10^oN) and the south eastern equatorial Indian Ocean (90^oE-110^oE and 10^oS-0^oN). The DMI was towards positive side of its normal value just prior to the monsoon season 2021 (since November 2020). It is seen from the Fig.2.4 that, weak negative IOD event has observed before the monsoon season, thereafter a rapid strengthening of IOD observed during initial part of the monsoon season. The atmosphere also responds for the SST features associated with IOD features in the month of June over the Indian Ocean. The 2021 IOD event was short lived and it reached to the neutral state before end of the August month and neutral state of IOD was continued till September. Thus, monsoon circulation was influenced by weak negative IOD conditions were observed during first part of the 2021 monsoon season.

2.2 OLR anomalies

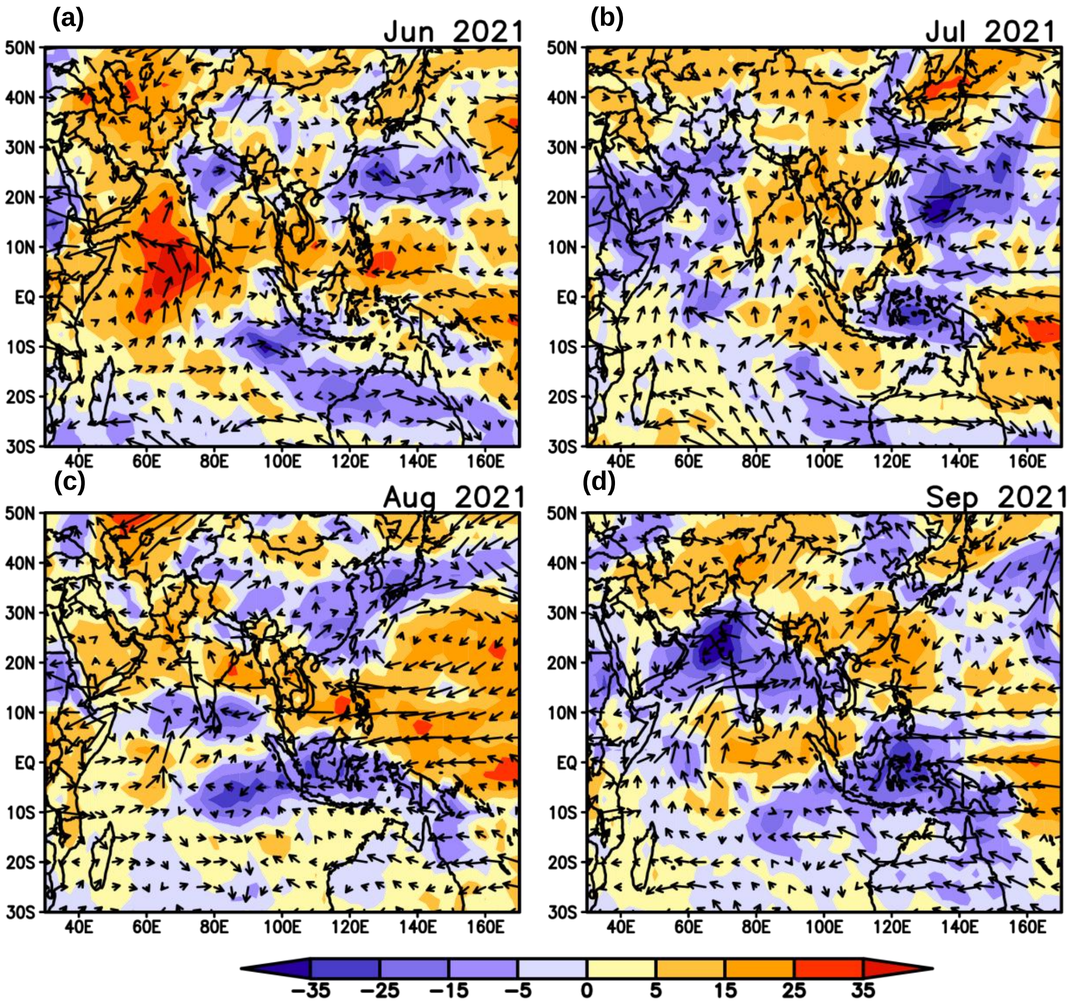

Fig. 2.5 Monthly OLR anomalies (shaded) and Wind Anomalies at 850 hPa (vector) during a) June b) July c) August and d) September 2021.

Spatial distribution of monthly Outgoing Long Wave Radiation (OLR) anomalies during June to September is shown in Fig. 2.5 (a, b, c, d). The negative (positive) OLR anomalies indicate above (below) normal convection. In the month of June, positive OLR anomalies were observed over most parts of Arabian Sea and many parts of Bay of Bengal as well as southwest and extreme southeast Indian Ocean. The magnitude of maximum positive anomaly more than 25 W/m^2 observed central parts of Arabian Sea. The negative OLR anomalies were also observed over most parts of central India adjoining south peninsula, east and northwest India. The positive OLR anomalies are observed over parts of north and northeast India. The positive OLR anomalies over equatorial west Pacific and along equatorial Indian

Ocean indicated below normal convection over that region. As a whole June month has shown enhanced convective activity over most parts of India.

During the month of July, the negative OLR anomalies were observed over parts of northwest India and neighboring region of central India,most parts of western coast and adjoining interior parts of central India as well as most parts from south peninsula. Negative anomalies were also observed over many parts of Arabian Sea. A positive OLR anomaly was observed over parts of centralIndia, adjoining parts of east India and most parts of northeast India.Positive anomalies were also observed over most parts of Bay of Bengal along with east coast region. As a whole, the July OLR anomaly pattern over Indian region showed enhanced convective activity over western region of India and suppressed convective activity over remaining parts of the country. In the month of August, the positive OLR anomalies observed over most of Indian region except southern peninsula and foothills of Himalayas. This indicates monsoon trough was towards north of its normal position during the mosttime of the Augustmonth. Negative OLR anomalies were observed over southern parts and positive OLR anomalies over remaining parts of the Arabian Sea and Bay of Bengal.In addition, negative OLR anomalies were also observed over Northwest Pacific region which indicated convection over the region. Overall suppressed convection pattern was observed over most parts of the India during the month of August. During September, convective activity is seen strengthened over most parts of India and negative OLR anomalies wereobserved over entire India except most parts of north and north east India. Negative OLR anomalies were also observed over most parts of Arabian Sea and Bay of Bengal. The magnitude of maximum negative anomaly less than 25 W/m^2 observed northwest India and adjoining parts of north Arabian Sea. This convective pattern indicate that monsoon trough was south of its normal position during most time of the September which has contributed to the active monsoon over the region.

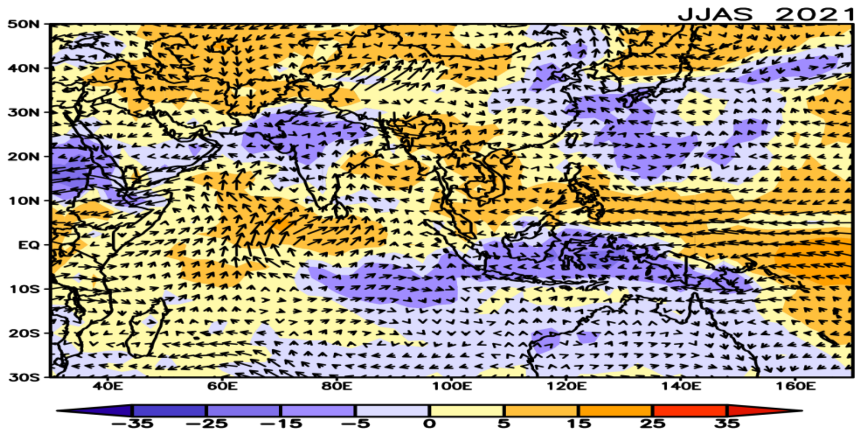

Fig. 2.6 OLR anomaly overlay with 850hPa wind during June to September 2021

The OLR anomalies averaged over the season (June to September) is shown in the Fig. 2.6. The season averaged OLR anomalies were negative over entire India except parts of north India and north east India. Also, above normal convective activity observed over the Northwest Pacific region with negative OLR anomalies in the seasonal average. The normal to negative OLR anomaly associated with neutral ENSO conditions (during first half of the season) and weak La Niña conditions (during second half of the season) over Indian subcontinent both were demonstrated in the season averaged OLR anomalies.

2.3 Lower and Upper Tropospheric Circulation Anomalies

The wind anomalies at 850 hPa for the month of June to September are shown in Fig. 2.5 (a, b, c, d). During June, the most prominent feature was the anomalous anticyclonic circulation over the Bay of Bengal and anomalous cyclonic circulation over northwest Pacific Ocean. Over Arabian Sea, southerly winds were observed during June, showing enhanced moisture incursion during the month. This might have contributed to the good rainfall activity during June. During the month of July, anomalous anticyclonic circulation was observed over south Peninsula. Over western parts of India and Arabian Sea, south westerlies were observed.Over northwest Pacific Ocean, weak cyclonic circulation was observed, so south westerly winds from Indian Ocean have travelled along with coast instead of main land area. With such situation, normal rainfall activity was observed during the month of July. During the month of August, anomalous anticyclonic circulation was observed over Bay of Bengal and adjoining areas from mainland India. Anomalous easterlies were observed over southern parts of India. However, much weaker than normal south westerlies were observed over some parts from northern India, it was due to shifting of monsoon trough over the foothills of Himalayas. Though easterlies were also established (La Niña Like Pattern) over equatorial Pacific, but they couldn't support rainfall during August. A huge anticyclonic circulation was seen over the areas of northwest and equatorial Pacific. Due to all these reasons, August month shown subdued rainfall activity, as there was very less moisture supply and disorganized monsoon winds were prevailed during the month. During September month, strongly organized south westerlies were visible over most parts of India. Anomalous south easterlies were visible over foothills of Himalayas. This indicates the organized monsoon trough which was remained to south of its normal position during most time of the month. However, anomalous anticyclonic circulation was observed over north eastern parts of India contributing subdued rainfall activity over the region. Over equatorial Pacific easterlies were observed, indicating La Niña like pattern over the region. Thus, during September, enhanced rainfall activity was observed over the Indian region.

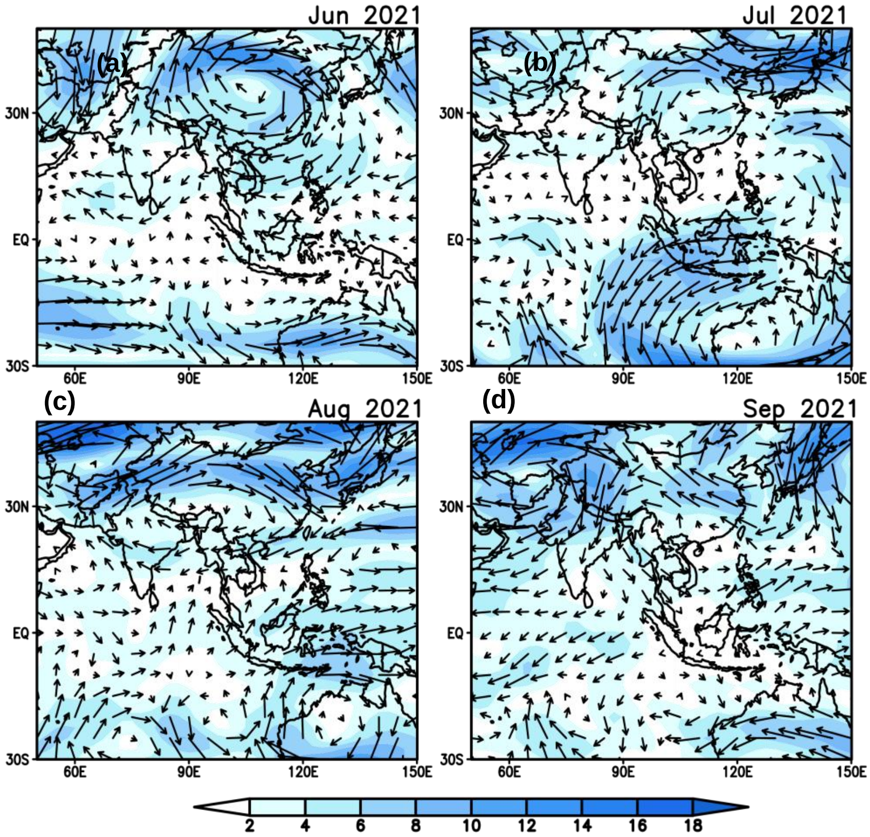

Fig. 2.7.: Wind Anomalies at 200 hPa during a) June b) July c) August d) September 2021.

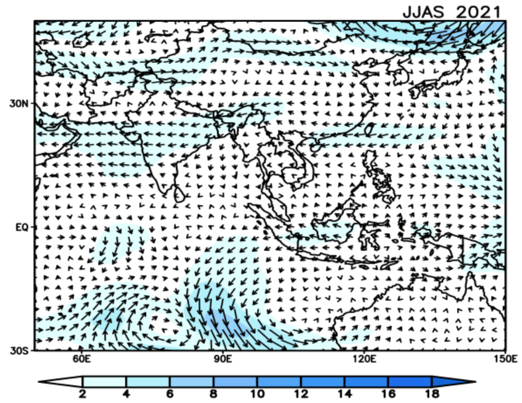

Fig. 2.8 Wind anomalies at 200 hPa during monsoon season (June to September) 2021

The Fig. 2.7 (a, b, c, d), show wind anomalies at 200 hPa. In June, strong anticyclonic circulation located near the Tibetan Plateau, indicates that one of the major semi-permanent feature i.e. Tibetan High was very prominent during June. Its position found normal. As a result, Tropical Easterly Jet stream (TEJ) was also found well established. In July, anticyclonic circulation over Tibetan plateau and surrounding region is shifted north of its normal position and TEJ was slightly distorted. In addition to this, an anomalous cyclonic circulation prevailed over northeast south Asia and one more anomalous cyclonic circulation over northern parts of South Asia, westerlies associated with it prevailed over northern parts of India in the month of July. During the subsequent month of August, spread of Tibetan anticyclone was larger and position of Tibetan High is shifted towards south and an anomalous upper air anticyclonic circulation was observed over northwest parts of India and neighboring region. An anomalous cyclonic circulation was seen over northwest Pacific and adjoining areas. As a result of it anomalous westerly wind observed over extreme southern parts of India. Overall upper air wind pattern indicates weakenedTEJ during August month. In the month of September, position of Tibetan high was observed westwards of its normal position. Its intensity also was stronger in the September than all other months during the monsoon season. As a result, strong TEJ was seen over entire India during September. However, northerly wind component was prevailing during the month over most parts of India. There were no strong anomalous cyclonic or anticyclonic circulation observed over the Pacific Ocean. This was indication of enhanced monsoon activity over India.

The wind anomalies averaged over the season (June to September) is shown in the Fig. 2.6 (850 hPa) and Fig. 2.8 (200 hPa). In the season averaged (June-

September) 850 hPa wind anomaly (Fig. 2.6) it has observed that strong cross equatorial flow from south Indian Ocean and strong low level Jetstream during the monsoon season over the central and northwest India. It can also be observed that southeasterly or southerly winds coming from Bay of Bengal and Arabian Sea might have brought lot of moisture in the mainland India during entire season. However, over northeastern parts of the country, anomalous northerly winds causing subdued monsoon activity during the season. In the season average, organized and stronger than normal 200 hPa easterly wind (Fig. 2.8) were found. Strong TEJ indicate the enhanced monsoon circulation during 2021 SW monsoon season for most of the time.

2.4 Meridional and Zonal Circulation Anomalies over Indian Region

To examine the changes in the meridional circulation over Indian region during the monsoon season, latitude-height cross section of vertical velocity (omega) anomalies averaged over longitudinal zone of 70^{o}E-90^{o}E was plotted for the monsoon season (Fig.2.9). It can be seen that there is a one anomalous meridional circulation cell over north Indianregion, having strong descending branch over north of about 25^{o}N. There is also a weak anomalous meridional circulation havingascending branch over the south of latitude 20^{o}N. Another strong meridional cell with its ascending branch between equator to 10^{o}S and descending branch over south of 10^{o}N was also observed. These indicate overall,rising motion prevailed in the Indian region during the monsoon season and in supporting enhanced rainfall activity during season, conditions were also seen favorable in the large scale circulation pattern over maritime continent and surrounding region. Fig. 2.10 (a, b, c, d) which depict the monthly meridional circulation anomaly over Indian monsoon region during June to September. It can be seen that the strength of the descending motion near latitude 30^{o}N observed during June was persistent in the subsequent months. A strong ascending branch was observedover south of 30^{o}N during all the months expect August month. During August, descending branches were extended up to Equator towards south of 5^{o}N. This contributed unfavorable vertical circulation over the Indian region during the period. However, during September magnitude of rising motion (ascending branch) has been increased anomalously over and around

20^oN. This favorable vertical circulation causedabove normal convective activity and resulted inexcess rainfall during September month.

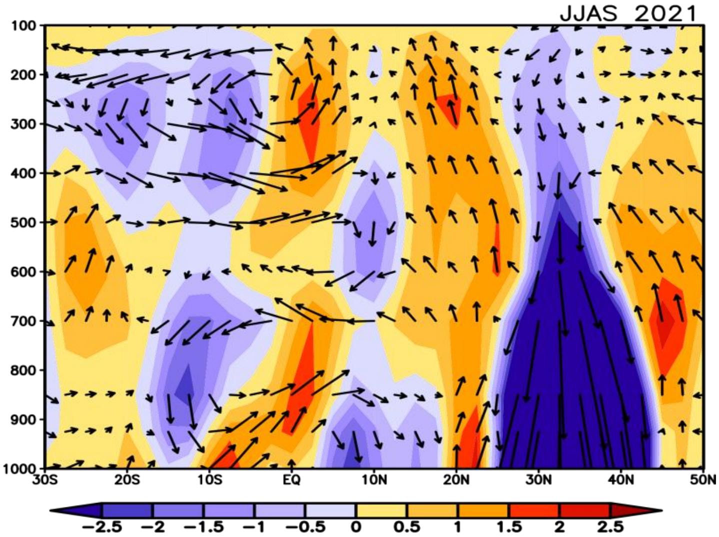

Fig. 2.9 Vertical cross-section of Pressure vertical velocity overlay with Meridional vertical circulation for the monsoon season (June-September 2020). Pressure vertical velocity (Omega) are shaded. The anomalies are averaged over longitudes 70^oE to 90^oE.

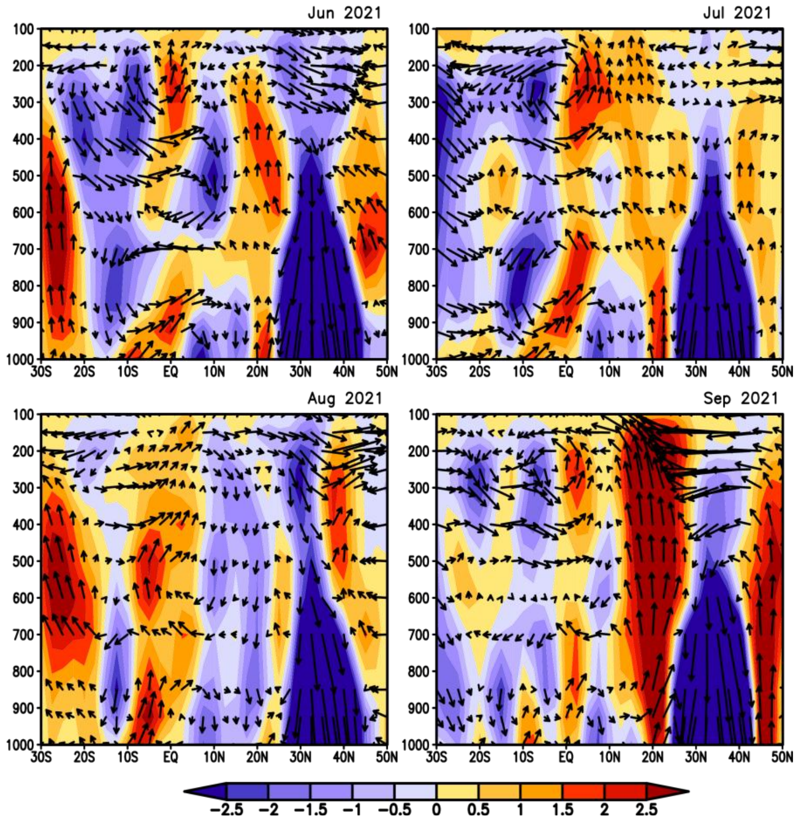

Fig. 2.10 Latitude Height Circulation Cross-section and Omega during a) June and b) July c) August andSeptember 2020. Pressure vertical velocity (Omega) are shaded The anomalies are averaged over longitudes 70^oE-90^oE.

A zonal vertical circulation anomaly over the Indian region during the monsoon season, longitude-height cross section of vertical velocity (omega) anomalies averaged over longitudinal zone of 15^{o}N-25^{o}N was plotted for the monsoon season (Fig. 2.11 a, b. c. d). Overall, there was not any strong anomalous descending motion observed over Indian region during entire monsoon season except the month of August. In the month of June and July weak descending motion observed over the west Indian Ocean and west Pacific Ocean. During August, strong descending branches were observed over many areas of Indian region. During September, again strong ascending branch established and shifted further east. There was an increase in strength of descending motion over the north east Indian region during all the months before which weakened slightly in the month of September.

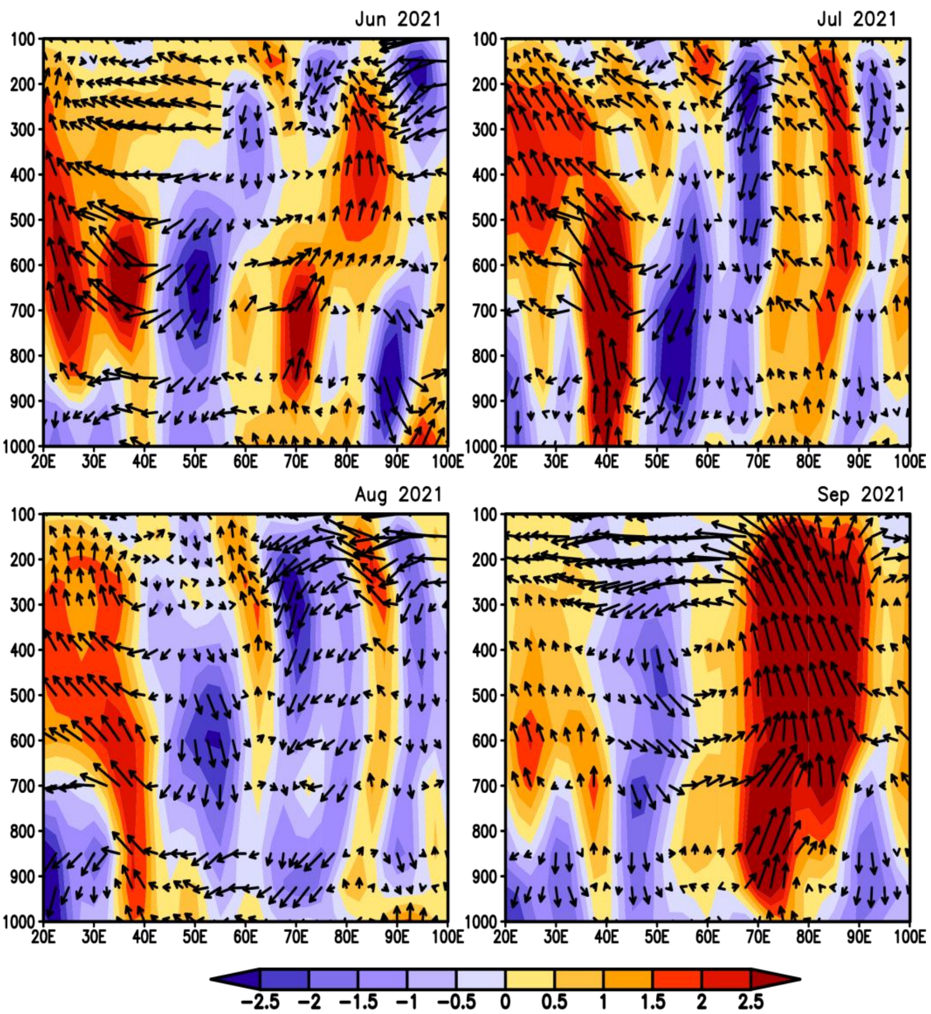

Fig. 2.11 Longitude Height Circulation Cross-section and Omega during a) June and b) July c) August and September 2020. Pressure vertical velocity (Omega) are shaded The anomalies are averaged over longitudes 15^{o}N-25^{o}N.

2.5. Intra-seasonal Variability during the Monsoon Season

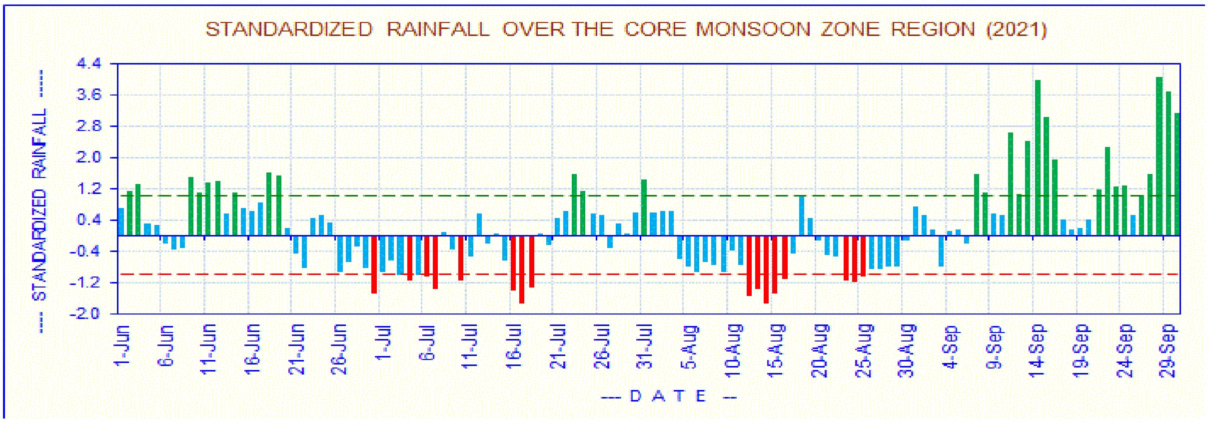

Fig. 2.12 Time series of standardized Rainfall anomaly for core monsoon zone during the monsoon 2021.

The intra-seasonal variation of rainfall during 2021 monsoon season is depicted in the Fig. 2.12, which shows the time series of daily rainfall anomaly over the core monsoon zone (Rajeevan et al, 2010). It can be seen that, weak monsoon situation observed during most daysin July and August month. It can be also seen that, during August, the negative rainfall anomaly was observed most of the days and break monsoon like situation during middle and end of the month. Overall, June and September received above normal rainfall, August received below normal rainfall and July received normal rainfall of the season.

2.6. Typhoon activity over west Pacific

The west Pacific typhoon activity is also one of the important factor responsible for subdued rainfall activity over North East Indian Region (Muley and Shukla, 1989). There were many previous studies have discussed relationship between Indian summer monsoon rainfall and typhoon activity over west Pacific (Rajeevan et al 1993, Vinay Kumar et al 2005, and Pattanaik and Rajeevan 2007). It may be noted that the typhoon activity over west Pacific Ocean during this monsoon season had a slow start initially in the month of June and then it has started increasing from July. However, again in September, the activity was reduced as compared to the August. There were 25 Low pressure system formed over the west Pacific during the season, out of 5 systems became typhoon category. The tracks of the systems formed during the season (June to September) given in the Fig 2.13. It can be seen that most of the systems were showing re-curving tracks (especially in the month of August) in west Pacific and formed east of 130^{o}E which has negative impact on Indian summer monsoon rainfall. In the month of August, not a single system has propagated towards Bay of Bengal region and thus it adversely affects the formation of Low pressure system over Head Bay. However, typhoon formed over south China Sea and moving westward has helps the formation of Low-Pressure system which is having a positive impact on summer monsoon rainfall, which were in some cases from June and September. One of the factors for the reduced rainfall activity during the month of August is a smaller number of Low-Pressure systems formed in the Head Bay of Bengal mainly due to a less number of typhoon remnants propagated westwards and induced genesis of monsoon lows over the Indian region.

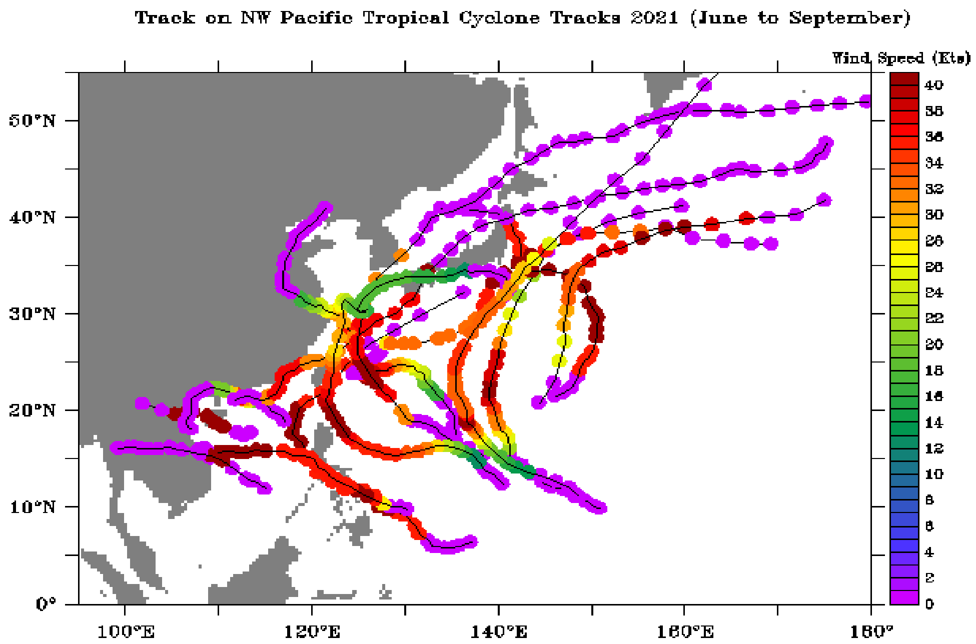

Fig. 2.13Observed tracks of the Typhoons formed over North West Pacific Ocean during June to September months for the year 2021. (Data source: Best track data JMA).

2.7. Important Global and Regional features that influenced the Rainfall pattern over Indian Region

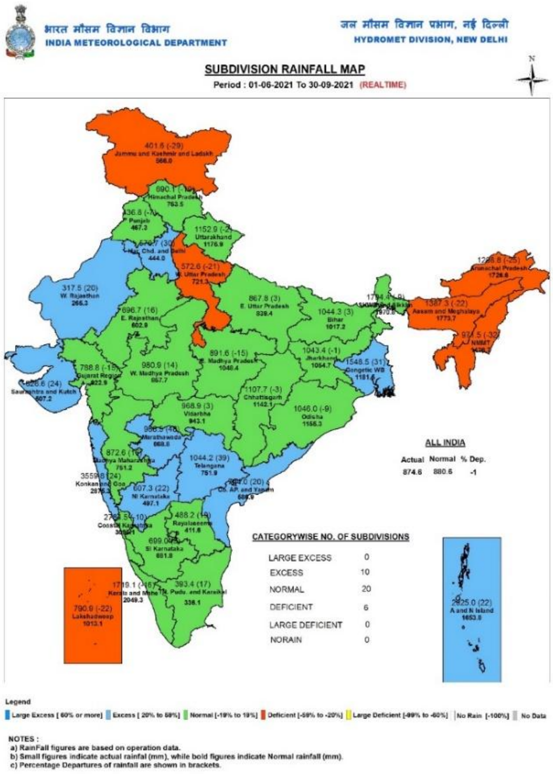

Fig.2.14 Sub-divisional rainfall map of 2021 monsoon season.

Out of the total 36 meteorological subdivisions of India, 20 subdivisions constituting 58% of the total area of the country received normal seasonal rainfall, 10 subdivisions received excess rainfall (25% of the total area) and 6 subdivisions (17% of the total area) received deficient season rainfall (Fig.2.14). These 6 Met subdivisions which got deficient rainfall are Nagaland, Manipur, Mizoram & Tripura, Assam and Meghalaya, Arunachal Pradesh, Jammu & Kashmir and Ladakh, West Uttar Pradesh and Lakshadweep. Out of these six Subdivisions, three lie in northeast India. Two Met Subdivisions which got much higher than normal rainfall in the season are Marathawada and Telangana. Considering month to month rainfall variation over India as a whole, the season is very uniquely placed in the historical record for its distinct and contrasting month to month variation. The rainfall over country as a whole was 110%, 93%, 76% and 135% of LPA during June, July, August and September respectively. The actual rainfall over Northwest India, Central India, Northeast India, South Peninsula and Monsoon Core Zone were 96%, 104%, 88%, 111% and 107 % of the LPA respectively.

Based on spatial and temporal rainfall anomaly figures, seasonal rainfall pattern can be summarizing as;

i) The season rainfall was normal/excess over most part of the country except 6 subdivisions.

ii) The seasonal rainfall was normal/excess over 83% of the total area of the country.

iii) There was intra-seasonal fluctuation contributed by synoptic systems observed during the monsoon season.

iv) The spatial rainfall distribution was fairly well distributed during the monsoon season.

v) The maximum rainfall deficiency was observed during the August month.

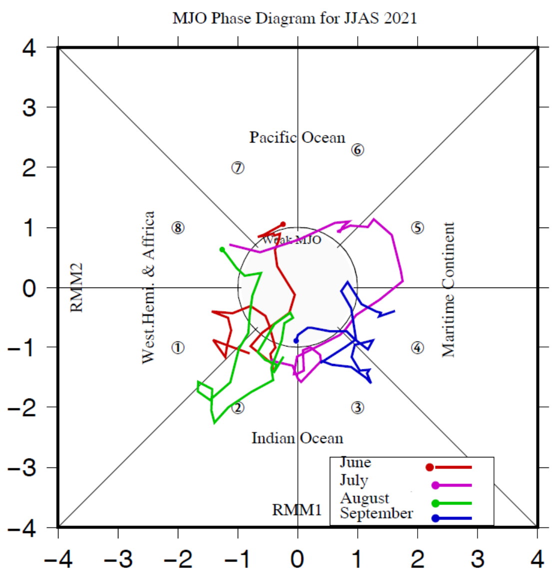

Fig. 2.15 The Phase-space diagram depicting MJO index during monsoon season 2021. The encircle number inside 8 sectors of the diagram represent 8 Phases of MJO in the diagram.

The Madden Julian Oscillation (Wheeler and Hendon, 2004) (MJO), has significant influence on the monsoon intra-seasonal variability (Pai et al, 2009). This year MJO has remained active with moderate to strong signal during most part of the monsoon season except in some part of June and some part from the month of August (Fig. 2.15). During June it was active over Western Hemisphere and Indian Ocean which was quite favorable for cyclogenesis over Arabian Sea and pulling monsoon current from south to north. It was also favorable for monsoon onset activity over Kerala. During July, it was seen active over the Maritime Continent and for some period over western Pacific Ocean. During August it was completely in the unfavorable phase of Monsoon that is over Western Hemisphere and Africa and western Indian Ocean (phase 8, 1 and 2) for some time and later found weak. During September, MJO was active over east Indian Ocean and Maritime Continent. So, substantial effect of MJO was seen during June to September 2021 monsoon season. Also, it has supported Onset Activity Over Arabian Sea during the season start.

Sea surface temperature (SST) anomalies from Indian Ocean and Pacific Ocean have significant impact on performance of Monsoon season over Indian region. From Fig.2.16 (b), it is seen that, throughout June to August months during negative Indian Ocean Dipole (IOD) years, in general, many parts of the country, especially western and eastern parts of India and some areas from east and northeast India receives below normal rainfall (refer Negative IOD years composite figure 2.16(a)). During 2021, since month of May (Fig.2.4), negative IOD was observed over Indian Ocean. It was continued up to August. Because of this, southwest monsoon performance was hindered and overall spatial and temporal distribution of rainfall was unbalanced. Therefore, during 2021 southwest monsoon season, in the months of July and August monsoon activity was slightly subdued, however negative IOD event was short lived. Whereas, due to La Niña conditions over Pacific Ocean, the negative impact on rainfall of IOD event was compensated during the subsequent month of September.

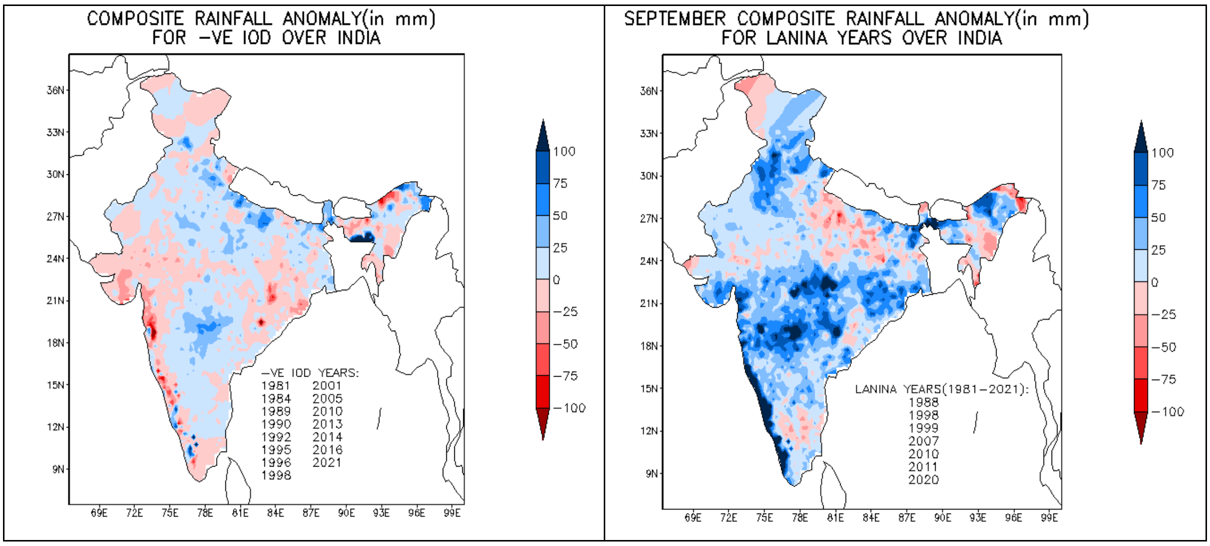

Fig. 2.16(a) Rainfall anomaly composite for period 1980 to 2021 during Negative IOD Years June to August period (b) Rainfall anomaly composite for period 1980 to 2019 during La Niña Years September month.

From Fig.2.16(b), it is seen that, in the September month during La Niña years, in general, many parts of the country receive normal to above normal rainfall and few parts from east receives below normal rainfall (refer La Niña composite figure 2.16(b)). Though ENSO was in the neutral state during initial part of the monsoon season, the cooler SSTs over the equatorial Pacific started increasing in the later part of monsoon season. By the end of August month, cooler SSTs over Nino3.4 region started strengthening and weak La Niña was established over the Pacific along with responding atmospheric La Niña like pattern over the region during the month of September. Therefore, during 2021 southwest monsoon season, in the months of June, July and August there was not noticeable effect of ENSO conditions over monsoon (Fig. 2.17(a) to (c)), however in its subsequent month this effect has stated increasing, i.e. during September 2021. As we know, La Niña conditions are favorable for normal or above normal monsoon and during 2021 also, La Niña has supported above normal rainfall during the September month (Fig.2.17(d)).

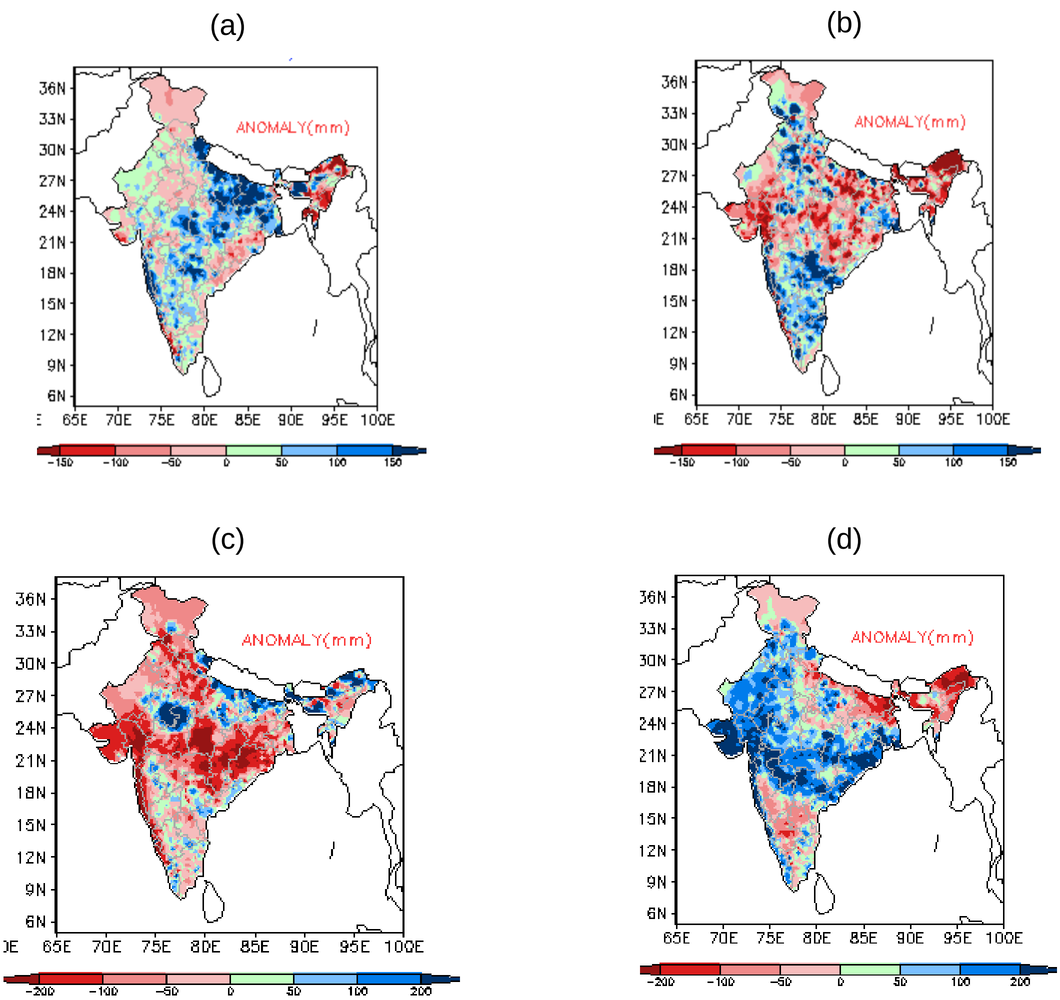

Fig. 2.17 Rainfall anomalies for (a) June (b) July (c) August and (d)September 2021

2.8. Summary

Southwest monsoon 2021 was normal in terms ofseasonal monsoon rainfall. Though less number of monsoon disturbances in the Bay of Bengal this year and insignificant MJO forcing, the monsoon has got impact from large scale forgings like Indian Ocean and Pacific Ocean SSTs. During the 2021 southwest monsoon season, in the month of June, weaknegative IOD conditions were established over Indian Oceanand IOD index turned in to neutral condition during the September, however, it has impacted significantly on August month rainfall.However, the large-scale SST forcing from Pacific Ocean were prominent during September month as strengthening of La Niña conditions was observed,and its effect was quitesignificant (Saji et al, 2007).Such intra-month variation of rainfall within a season can occur due to the fluctuation of SST anomalies in the Indian Ocean and Pacific Ocean (Ratna et al., 2021). As a result, influence on the monsoon from the large-scale SST forcing from Indian Ocean and Pacific Ocean were prominent during most part of the season.In addition,there are some other synoptic scale factors and intra-seasonal variations dominated the rainfall during the monsoon season.This year monsoon season has observed intra-seasonal variations associated with formation of monsoon low pressure systems and Northwest Pacific typhoon activity. One of the major tropical intra-seasonal variations associated with the MJO, was remained in the unfavorable phases during the most partmonsoon season except few days in the month of July and September, so the influence of MJO was seen during 2021 monsoon season. The rainfall especially in the month of August was alsoattributed to the less formation of low-pressure system over Indian region. The above normal rainfall over the central and adjoining parts of the India during the September was also attributed to the active monsoon trough which was remained to south of its normal position most of the times as well as formation of more number of lows. Thus, the rainfall deficiency was more during the August and in its subsequent months like September, excess rainfall activity was observed. However, the spatial rainfall distribution was fairly well distributed during the monsoon season.

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3

ANALYSIS OF SYNOPTIC SCALE EVENTS ASSOCIATED WITH HEAVY RAINFALL OVER NORTHWEST INDIA DURING 2021SW MONSOON SEASON

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Regional Meteorological Centre, New Delhi

3.1 HIGHLIGHTS

- **Seasonal rainfall over Northwest India was 96% of its LPA.**
- **Seasonal rainfall was 180% of its LPA over Delhi.**
- **Monthly rainfall over Delhi was 53% of LPA in June, 241% in July, 87% inAugust and 330% in September.**
- **Southwest monsoon advanced over Kerala on 03rdJune and over Rajasthan on 18th June (2 days ahead the normal schedule of 20th June). Thereafter, monsoon covered the entire northwest India by 13th July against normal date of 08th July (about 5 days behind of normal date).**
- **Monsoon withdrawal commenced from Northwest India from 6th October. It was completely withdrawn from Northwest India by 8th October 2021.**

3.1.1Onset and Advance of southwest Monsoon

This year SW monsoon advanced into some parts of south Rajasthan on 18thJune, subsequently it advanced over some more parts of south Rajasthan on 19thJune. Large scale atmospheric features, weak cross equatorial flow and dominance of dry westerly winds over major parts of the Rajasthan affected further progress of monsoon and remained stagnant for 22 days when there was no further advance. The absence of major low pressure systems over Bay of Bengal and Arabian Sea results weak monsoon in the first half of July.

After 10thJuly, gradual strengthening of monsoon flow and incursion of moist easterly winds from Bay of Bengal upto Northwest India by deepening of seasonal monsoon trough results further progress of monsoon over remaining parts of the state. The monsoon covered entire Rajasthan by 13thJuly against normal date of 8thJuly (about 5 days behind of normal date).

3.1.2 Withdrawal of southwest Monsoon

Establishment of westerly & northwesterly winds at lower & middle tropospheric levels over northwest India and development of lower level anti-cyclonic circulation over the region from 5thOctober, 2021. These results in drastic reduction in moisture and absence of clouds and rainfall over extreme northwestern parts of India. Under its influence, Monsoon withdrawal commenced from Northwest India from 6thOctober. It was completely withdrawn from Northwest India by 8thOctober, 2021.

Rainfall Distribution over Northwest India during Southwest Monsoon from01.06.2021 to30.09.2021

Fig 3.1.1: Distribution of Cumulative Rainfall during southwest monsoon 2021 over Northwest India.

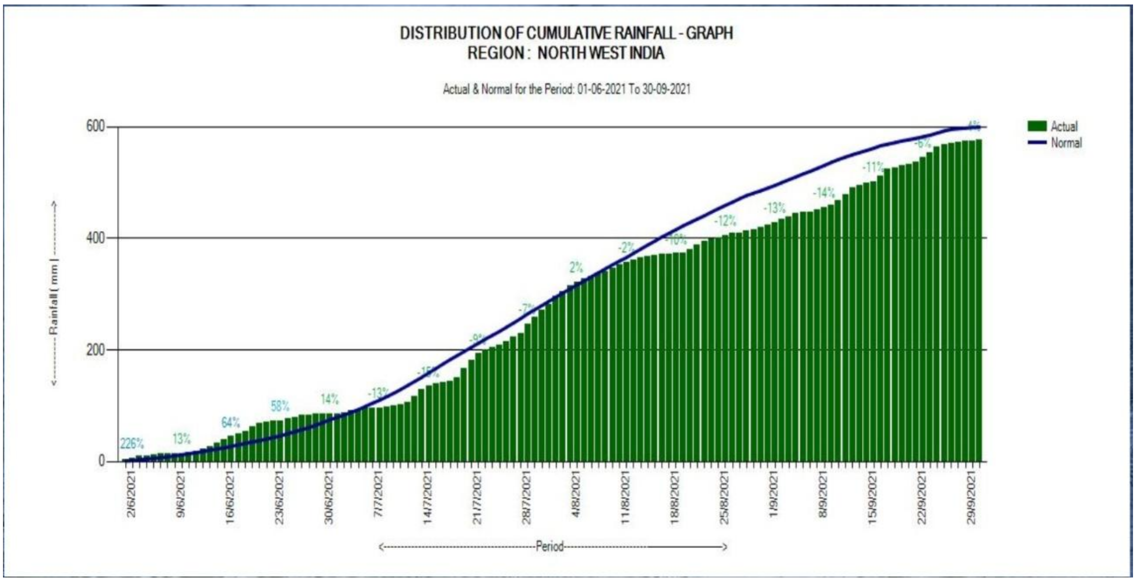
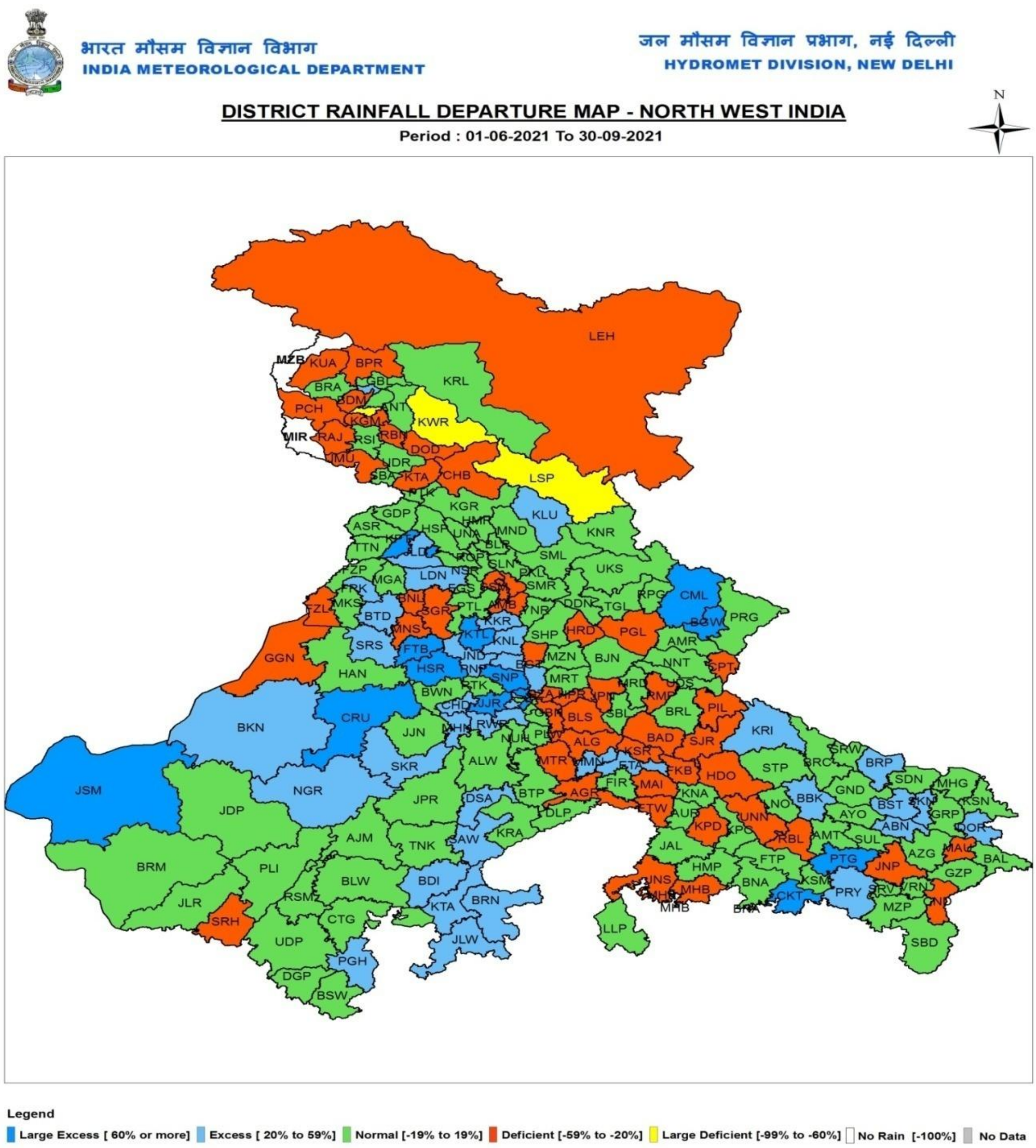


Table 3.1.1: Subdivision wise Actual and Normal Rainfall with their departure during southwest monsoon 2021

SUBDIVISION/ DIVISION	ACTUAL R/F (MM)	NORMALR/F (MM)	DEPARTURE (%)
Jammu & Kashmir	401.6	566.0	-29
Himachal Pradesh	690.1	763.5	-10
Uttarakhand	1152.9	1176.9	-02
Punjab	436.8	467.3	-07
Haryana	576.7	444.0	30
West Uttar Pradesh	572.6	721.3	20
East Uttar Pradesh	867.8	839.4	16
West Rajasthan	317.5	265.3	-21
East Rajasthan	696.7	602.9	03

Fig 3.1.2: District wise Rainfall departure map-Northwest India



3.1.4: Rainfall Distribution over Delhiduring Southwest Monsoon from 01.06.2021 to 30.09.2021

Table3.1.2: District wise Actual and Normal Rainfall during southwest monsoon 2021

SUBDIVISION/ DISTRICT	ACTUAL	NORMAL	DEPARTURE (%)
DELHI (UT)	745.2	585.8	27
CENTRAL DELHI	1273.3	674.9	89
EAST DELHI	723.6	674.9	07
NEW DELHI	921.1	517.7	78
NORTH DELHI	1183.3	590.8	100
NORTH EAST DELHI	500.6	674.9	-26
NORTH WEST DELHI	728.5	488.8	49
SOUTH DELHI	671.2	674.9	-01
SOUTH WEST DELHI	808.7	596.6	36
WEST DELHI	590.2	621.7	-18

Table3.1.3: Month wise Actual and Normal Rainfall over Delhi during southwest monsoon 2021

Month	Actual (in mm)	Long period average LPA (in mm)
June	34.8	65.5
July	507.1	210.6
August	214.5	247.7
September	413.3	125.1

- **Monthly rainfall over Delhi was 53% of LPA in June, 241% in July, 87% in August and 330% in September.**

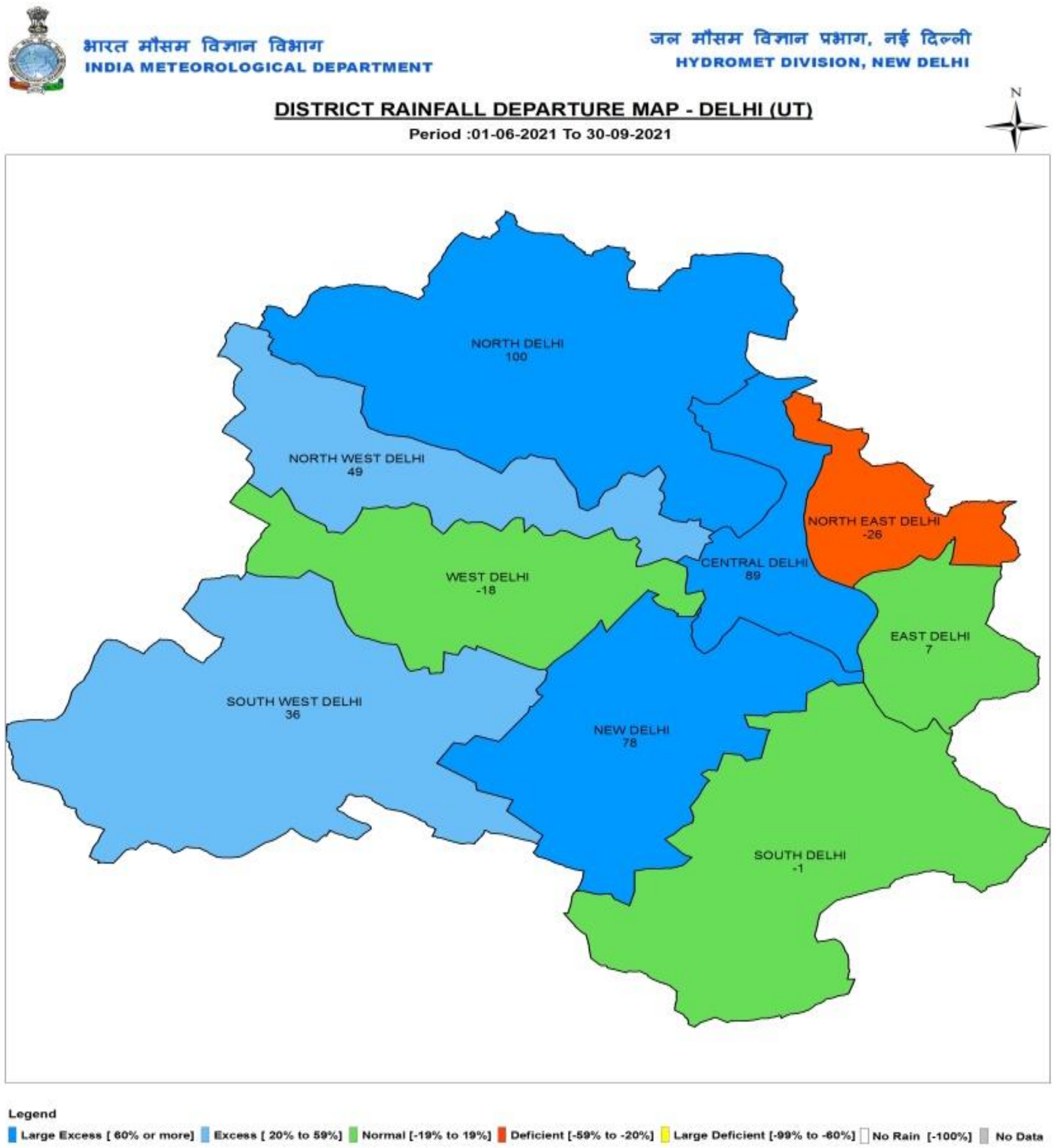


Fig 3.1.3: District wise Departure in Rainfall during southwest monsoon 2021

Table 3.1.4: Heavy Rainfall over Delhi during Monsoon Season 2021

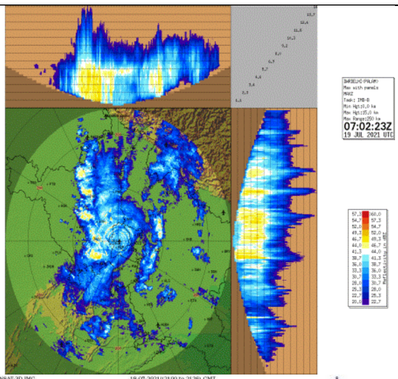
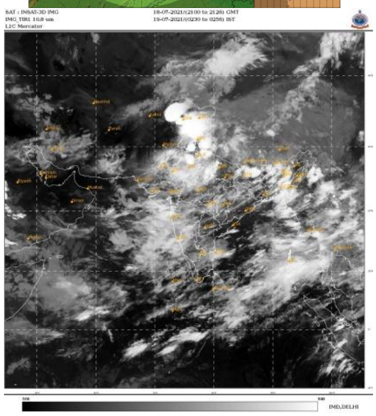
List of stations which reported heavy rainfall (>64.5 mm in 24 hours) during SW Monsoon.		
DATE	**PLACE**	**AMOUNT OF RAINFALL (in mm)**
15/07/2021	**DELHI UNIVERSITY (NORTH DELHI)**	**85.8**
	PITAMPURA AWS (NORTH WEST DELHI)	**87.5**
19/07/2021	**PUSA AWS (CENTRAL DELHI)**	**74.8**
	SAFDARJUNG (NEW DELHI)	**69.6**
	NARELA (NORTH WEST DELHI)	**104.0**
	DHANSA (SOUTH WEST DELHI)	**95.4**
	PALAM (SOUTH WEST DELHI)	**99.3**
	NAJAFGARH (WEST DELHI)	**95.0**
20/07/2021	**PUSA AWS (CENTRAL DELHI)**	**76.0**
	DHANSA (SOUTH WEST DELHI)	**79.5**
	PALAM (SOUTH WEST DELHI)	**67.6**
	NAJAFGARH (WEST DELHI)	**79.5**
27/07/2021	**PUSA AWS (CENTRAL DELHI)**	**82.6**
	LODI ROAD (NEW DELHI)	**85.8**
	SAFDARJUNG (NEW DELHI)	**100.0**
	AYANAGAR (SOUTH DELHI)	**69.8**
	AYANAGAR AWS (SOUTH DELHI)	**75.5**
	DHANSA (SOUTH WEST DELHI)	**66.6**
	PALAM (SOUTH WEST DELHI)	**68.0**
29/07/2021	**DHANSA (SOUTH WEST DELHI)**	**85.4**
	JAFARPUR AWS (SOUTH WEST DELHI)	**133.0**
30/07/2021	**LODI ROAD (NEW DELHI)**	**74.0**
	SAFDARJUNG (NEW DELHI)	**72.0**
01/08/2021	**DELHI RIDGE (NORTH DELHI)**	**126.8**
	DELHI UNIVERSITY (NORTH DELHI)	**66.2**
	PITAMPURA AWS(NORTH VWEST	**90.5**

	DELHI)	
09/08/2021	PUSA AWS (CENTRAL DELHI)	67.4
21/08/2021	PUSA AWS (CENTRAL DELHI) SPS MAYUR VIHAR (EAST DELHI) LODI ROAD (NEW DELHI) LODI ROAD AWS (NEW DELHI) SAFDARJUNG (NEW DELHI) DELHI RIDGE (NORTH DELHI) DELHI UNIVERSITY (NORTH DELHI) SPORTS COMPLEX AWS PITAMPURA AWS(NORTH VWEST DELHI) AYANAGAR (SOUTH DELHI) AYANAGAR AWS (SOUTH DELHI) PALAM (SOUTH WEST DELHI)	112.8 99.0 149.0 101.0 138.8 149.2 113.4 124.5 113.5 68.2 67.5 84.0
01/09/2021	PUSA AWS (CENTRAL DELHI) LODI ROAD (NEW DELHI) LODI ROAD AWS (NEW DELHI) SAFDARJUNG (NEW DELHI) DELHI RIDGE (NORTH DELHI) SPORTS COMPLEX AWS (NORTH EAST DELHI) PITAMPURA AWS (NORTH VWEST DELHI) AYANAGAR (SOUTH DELHI) DHANSA (SOUTH WEST DELHI) PALAM (SOUTH WEST DELHI)	102.4 120.2 97.0 112.1 81.6 77.0 73.0 68.2 96.4 71.1
02/09/2021	PUSA AWS (CENTRAL DELHI) SPS MAYUR VIHAR (EAST DELHI) LODI ROAD (NEW DELHI) LODI ROAD AWS (NEW DELHI) SAFDARJUNG (NEW DELHI) DELHI RIDGE (NORTH DELHI)	173.4 84.0 133.6 79.0 117.7 68.4

	SPORTS COMPLEX AWS (NORTH EAST DELHI) PALAM (SOUTH WEST DELHI)	92.5 108.2
11/09/2021	PUSA AWS (CENTRAL DELHI) SAFDARJUNG (NEW DELHI) DELHI RIDGE (NORTH DELHI) DELHI UNIVERSITY (NORTH DELHI) PALAM (SOUTH WEST DELHI)	92.8 94.7 67.6 74.8 103.3
12/09/2021	PUSA AWS (CENTRAL DELHI) SPS MAYUR VIHAR (EAST DELHI)	74.0 69.0

3.1.5: Synoptic analysis and inputs from Radar and Satellite for heavy rainfall events over North West India 2021

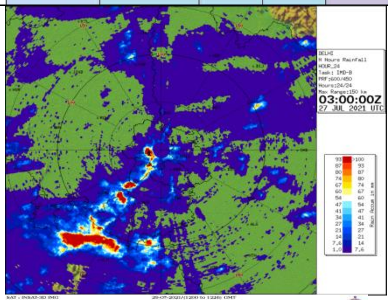
3.1.5.1: DELHI

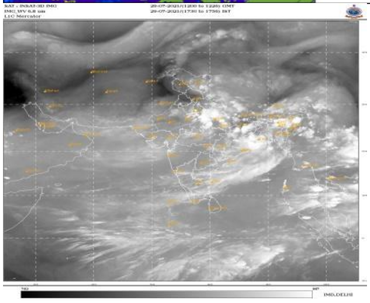
DATE	SYNOPTIC SITUATION	RADAR/SATELLITE IMAGES & 3-HOURLY RAINFALL
19/07/2021	• The Monsoon Trough at mean sea level passed through Ganganagar, Narnaul, Aligarh, Kanpur,Daltonganj,Shantiniketan, Cherrapunji and thence east wards to Nagaland and extends upto 0.9 km above mean sea level. • The cyclonic circulation over southwest Rajasthan &neighbourhood at 1.5 km above mean sea level become less marked. • A cyclonic circulation lay over North Pakistan and neighbourhood and extendedupto 1.5 km above mean sea level.	 

DATE / STATIONS	Cumulative Rainfall from 18 JULY 08:30 AM To 19 JULY 08:30 AM	18 JULY 2021					19 JULY 2021	
		08:30 IST to 11:30 IST	11:30 IST to 14:30 IST	14:30 IST to 17:30 IST	17:30 IST to 20:30 IST	20:30 IST to 23:30 IST	23:30 IST to 02:30 IST	02:30 IST to 05:30 IST
Safdarjung	069.6	000.0	000.0	TRACE	007.2	001.3	000.3	031.6
Palam	099.3	000.0	000.0	000.8	003.3	000.0	000.0	035.2
Lodi Road	062.0	000.0	000.0	TRACE	062.0			
Ridge	058.0	000.0	000.0	000.0	058.0			
Ayanagar	051.6	000.0	000.0	000.0	051.6			

27/07/2021

- The Monsoon Trough at mean sea level passed through Ganganagar, Hissar, Delhi, Aligarh, Fursatganj, Gaya, Bankura and thence southeast wards to North east Bay of Bengal.
- The Western Disturbance as a trough in mid tropospheric westerlies with its axis at 5.8 km above mean sea level ran roughly along Longitude 66°E to the north of Latitude 30°N.
- The cyclonic circulation over Northwest Rajasthan &neighborhood extending upto 1.5 km above mean sea level persisted.



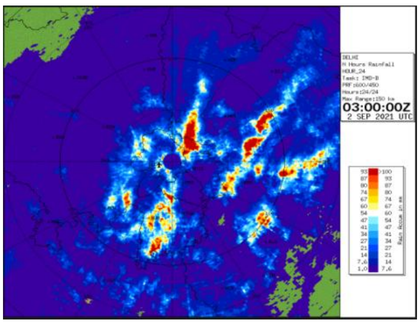


3 HOURLY RAINFALL (in MM) FOR DELHI

DATE / STATIONS	Cumulative Rainfall from 26 JULY 08:30 AM To 27 JULY 08:30 AM	26 JULY 2021					27 JULY 20	
		08:30 IST to 11:30 IST	11:30 IST to 14:30 IST	14:30 IST to 17:30 IST	17:30 IST to 20:30 IST	20:30 IST to 23:30 IST	23:30 IST to 02:30 IST	02:30 IST to 05:30 IST
Safdarjung	100.0	000.0	000.0	TRACE	000.0	000.0	000.0	000.0
Palam	068.0	000.0	000.0	000.0	000.0	000.0	000.0	007.4
Lodi Road	86.8	000.0	TRACE	000.0	86.8			
Ridge	38.2	TRACE	000.0	000.0	38.2			
Ayanagar	069.8	000.0	000.0	000.0	069.8			

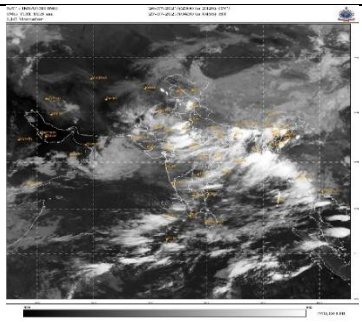
01/09/2021

- The monsoon trough at mean sea level now passed through Porbander, Surat, Jalgaon, Ramagundam, Machilipatnam and thence east-southeast wards to west central Bay of Bengal.
- The Western Disturbance as a trough in Lower & Middle tropospheric westerlies with its axis at 3.1 km above mean sea level ran roughly along



Long. 70°E to the north of Lat. 28°N.

- A trough in easterlies ran from cyclonic circulation over south Gujrat region and neighbourhood to northwest Uttar Pradesh across east Rajasthan and extendedupto 1.5 km above mean sea level.



Time of Issue: 0850 IST

3 HOURLY RAINFALL (in MM) FOR DELHI

DATE / STATIONS	Cumulative Rainfall from 01 SEPTEMBER 08:30 AM To 02 SEPTEMBER 08:30 AM	01 SEPTEMBER 2021					02 SEPTEMBER	
		08:30 IST to 11:30 IST	11:30 IST to 14:30 IST	14:30 IST to 17:30 IST	17:30 IST to 20:30 IST	20:30 IST to 23:30 IST	23:30 IST to 02:30 IST	02:30 IST to 05:30 IST
Safdarjung	117.7	075.6	000.6	000.3	000.0	000.0	000.0	000.0
Palam	108.2	078.2	002.4	000.0	000.4	000.0	000.0	000.0
Lodi Road	133.6	075.4	000.4	000.0	057.8			
Ridge	068.4	050.0	002.0	000.0	016.4			
Ayanagar	056.2	044.8	000.6	001.0	009.8			

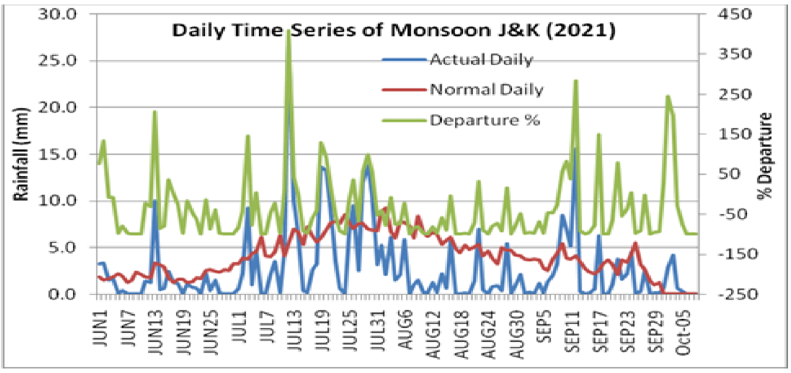
3.1.5.2: Monthly Rainfall Distribution over JAMMU & KASHMIR

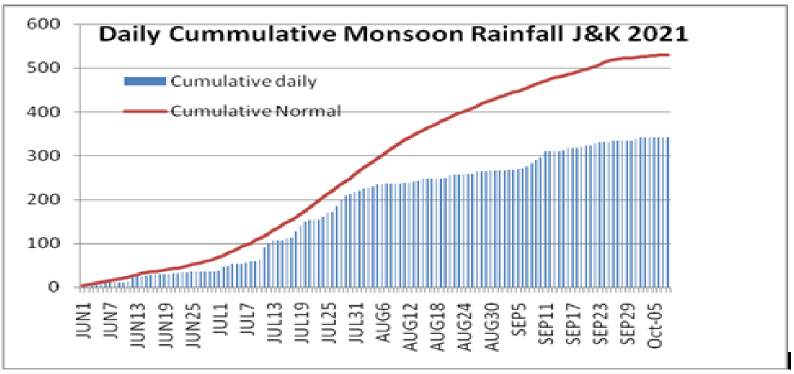
Monthly rainfall distribution for the month of June, July August and September and for first & second half of monsoon 2021 for J&K subdivision is shown below.

Months	Actual (mm)	Normal (mm)	% of LPA
June	38.2	73.9	52.0
July	212.0	205.0	103.41
August	74.1	185.3	40.0
September	77.0	103.4	74.75

Rainfall distribution in J&K.

The Jammu & Kashmir State received 411 mm of rainfall against its average of 573.4 mm with overall deficit of 28.3% during monsoon 2021.





3.1.5.3:Heavy Rainfall events during Monsoon 2021

Heavy to very heavy rainfall was observed in different stations of Jammu Division during 17-21st July, mainly Katra, Kathua and Udhampur. Very heavy showers were observed over Kathua on 19th July (121.8 mm). Similarly heavy to very heavy showers were also observed over Udhampur (78 mm on 17th July, 102 mm on 18thJuly and 108 mm on 21stJuly. Heavy to very heavy showers were observed over Udhampur (232.4 mm) and Jammu (132.4 mm) during 25th and 26th July. Heavy rainfall with high intensity rains and lightening 17-21 July which was highly localized rainfall resulted in flash floods in Jammu district and Poonch district of Jammu and Kashmir which resulted in killing of 3 buffaloes and dozens of animals were perished. Another heavy rainfall event with high intensity was reported on 29th July which was also highly localized resulted in 7death and 19 missing in Kishtwar cloudburst. Another heavy rainfall event with high intensity was reported during night of 11/12th August August over Baramulla (5 deaths &

1 injured) and Rajouri (1 Death) District and property damage to dozens of residential houses and huts. 1 person was also killed by severe lightening over Budgam on 20th August. Casualty and damage were reported from local newspapers and state authorities.

3.1.6.1:Highlights of Himachal Pradesh

- Monsoon advanced in all parts of HP on 13th June, 2021.
- Total Cumulative Rainfall during Monsoon season (i.e. from 1st June to 30th September, 2021) was 686.5 mm with departure of 10% less than the Long Period Average (763.5 mm).
- Chief rainfall: Shahpur: 264.0, Dharamshala:229.6, Palampur: 210.0 on 13th July, 2021.

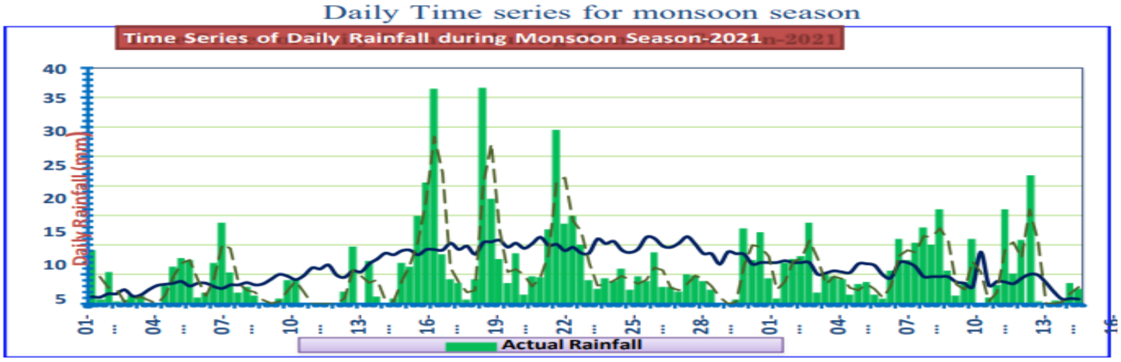
3.1.6.2: Monthly rainfall during southwest monsoon-2021

Monthly rainfall during south west monsoon-2021

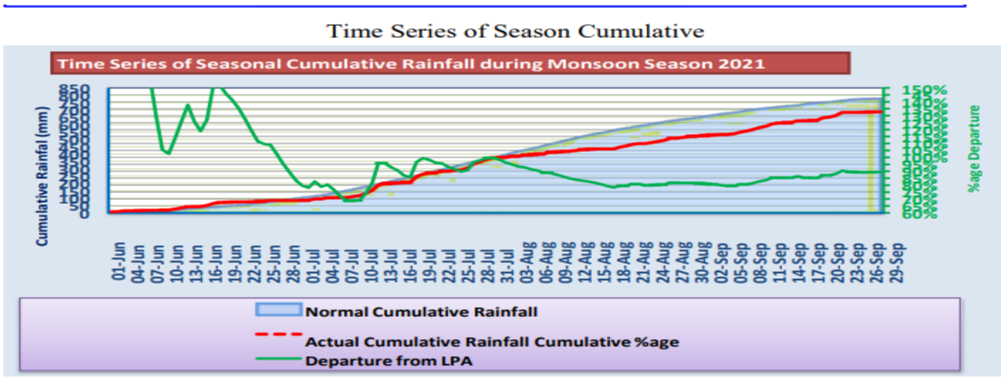
Month	Actual r/f (mm)	Normal r/f (mm)	% departure
June	84.6	100.5	-16
July	289.2	273	+06
August	146.5	262.3	-44
September	171.3	127.7	+34

3.1.6.3: Daily time series for Monsoon season

Daily Time series for monsoon season



3.1.6.4: Time series of season Cumulative



3.1.7.1: Highlights of Uttarakhand

For the state as a whole, the rainfall for the season (June-September) was 98% of its long period average (LPA) and thus categorized as a normal monsoon.

- Monthly rainfall over Uttarakhand as a whole was 148% of LPA in June, 91% of LPA in July, 77% of LPA in August and 110% of LPA in September respectively.
- Out of the total 13 districts of Uttarakhand, 02 districts received large excess, 08 districts received normal and 03 districts received deficient seasonal rainfall.
- Monsoon flow advanced over Uttarakhand and adjoining areas and Monsoon covered the entire State on the 13th June, 2021 (Onset).
- The monsoon activity over Uttarakhand was normal during the season (June-September).
- South-West Monsoon withdrew from the entire State on 8th October, 2021 (Withdrawal).

3.1.7.2: High Impact Events Observed During Sw Monsoon - 2021

Date	Synoptic Situation	Monsoon activity and significant rainfall (7 cm and above) (at 08:30 Hours IST. of Next Day)
17-Jun-21	• The Northern Limit of Monsoon (NLM) passed through lat.20.5°N/ Long. 60°E, Diu, Surat, Nandurbar, Bhopal, Nowgong, Hamirpur, Barabanki, Bareilly, Saharanpur, Ambala and Amritsar. • The Western Disturbance as a trough in mid &upper tropospheric westerlies with its axis at 5.8 km above mean sea level roughly along Long. 72°E to the north of	Light to moderate rainfall occurred at **most** places with heavy rainfall at isolated places in Uttarakhand. Thunderstorm occurred at isolated places (Dehradun) in Uttarakhand. Monsoon activity remained **VIGOROUS.**

	Lat. 22°N persisted.The trough from south Punjab to south Assam ran from West Rajasthan to northeast Bay of Bengal across northwest Madhya Pradesh, southeast Uttar Pradesh, south Bihar, Jharkhand and Gangetic West Bengal and extended upto 0.9 km above mean sea level. • A cyclonic circulation laid over south Pakistan &neighbourhood and extended upto 1.5 km above mean sea level. • A cyclonic circulation laid over south Haryana & neighborhood at 0.9 km above mean sea level.	**Haripur-8, Mukteshwar-7, Garud-7, Chamoli-7, Almora-7**
18-Jun-21	• The Northern Limit of Monsoon (NLM) passed through lat. 20.5°N/ Long. 60°E, Diu, Surat, Nandurbar, Bhopal,Nowgong, Hamirpur, Barabanki, Bareilly, Saharanpur, Ambala and Amritsar. • The cyclonic circulation over East Uttar Pradesh &neighbourhood extending upto 3.1 km above mean sea level persisted. • The Western Disturbance as a trough in mid & upper tropospheric westerlies with its axis at 5.8 km above mean sea level roughly along Long. 72°E to the north of Lat. 22°N persisted. • The trough from West Rajasthan to northeast Bay of Bengal across northwest Madhya Pradesh, southeast Uttar Pradesh, south Bihar, Jharkhand and Gangetic West Bengal extending upto 0.9 km above mean sea level persisted. • The cyclonic circulation over south Haryana &neighbourhood at 0.9 km above mean sea level persisted. • The cyclonic circulation over south Pakistan &neighbourhood extending upto 1.5 km above mean sea level persisted.	Light to moderate rainfall occurred at **many** places with heavy to very heavy rainfall at a few places in Uttarakhand. Monsoon activity remained **VIGOROUS.** **Nandkesari-17, Karnaprayag-15, Chamoli-14, Marora-13, Gairsain-13, Loharkhet-12, New Birahi-12, Nandprayag-12, Garud-11, Pauri-11, Jakholi-11, Ukhimath-11, Nainital-10, Srinagar-10, Mukteshwar-10, Joshimath-10, Keertinagar-9, Dhumakot-9, Tehri-9, Koteshwar-9, Ganganagar-9, Chaukhutia-9, Sama-9, Almora-8, Deoprayag-8, Haldwani-7, Bageshwar-7, Harshil-7, Dhanaulti-7, Chinyalisaur-7, Tharali-7, Dwarhat-7, Kapkot-7, Munsiyari-7, Lansdown-7, Pithoragarh-7, Betalghat-7**
19-Jun-21	• The northern Limit of southwest monsoon (NLM) passed through Lat. 26°N / Long. 70°E, Barmer, Bhilwara, Dholpur, Aligarh, Meerut, Ambala and Amritsar. • The Low pressure area over southeast Uttar Pradesh &neighbourhood with the associated cyclonic circulation extending upto mid tropospheric levels persisted. • The trough from West Rajasthan to northeast Bay of Bengal across south Haryana, centre of low pressure area over southeast Uttar Pradesh &neighbourhood, Jharkhand and Gangetic West Bengal extending upto 0.9 km above mean sea level persisted. • The Western Disturbance as a trough in	Light to moderate rainfall occurred at **most** places with heavy rainfall at isolated places in Uttarakhand. Thunderstorm occurred at isolated places (Mussoorie) in Uttarakhand. Monsoon activity remained **VIGOROUS.** **Haridwar-11, Champawat-9, Dharchula-9, Loharkhet-9, Sama-8, Lohaghat-8, Munsiyari-8, Pithoragarh-7, Nainital-7**

	mid & upper tropospheric westerlies with its axis at 5.8 km above mean sea level roughly along Long. 72°E to the north of Lat. 25°N persisted. • The cyclonic circulation over south Pakistan &neighbourhood laid over southwest Rajasthan &neighbourhood between 1.5 km&7.6 km above mean sea level tilting southwestwards with height. • The cyclonic circulation over north Rajasthan &neighbourhood laid over south Haryana &neighbourhood at 0.9 km above mean sea level. • A cyclonic circulation laid over southeast Rajasthan&adjoining West Madhya Pradesh between 3.1 km&4.5 km above mean sea level.	

3.1.7.3:RAINFALL DISTRIBUTION

The rainfall during SW monsoon season (June to September) for the State as a whole is as follows:

Met. Sub-division/ State	Actual Rainfall June-September (in mm)	Normal/Long Period Average (LPA) Rainfall June-September(in mm)	Departure from normal (in %)
Uttarakhand	**1156.1**	**1176.9**	**-2**

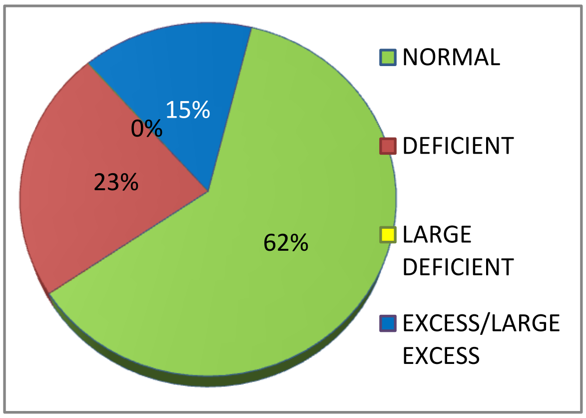


Fig3.1.7.1: INTENSITY DISTRIBUTION OF RAINFALL

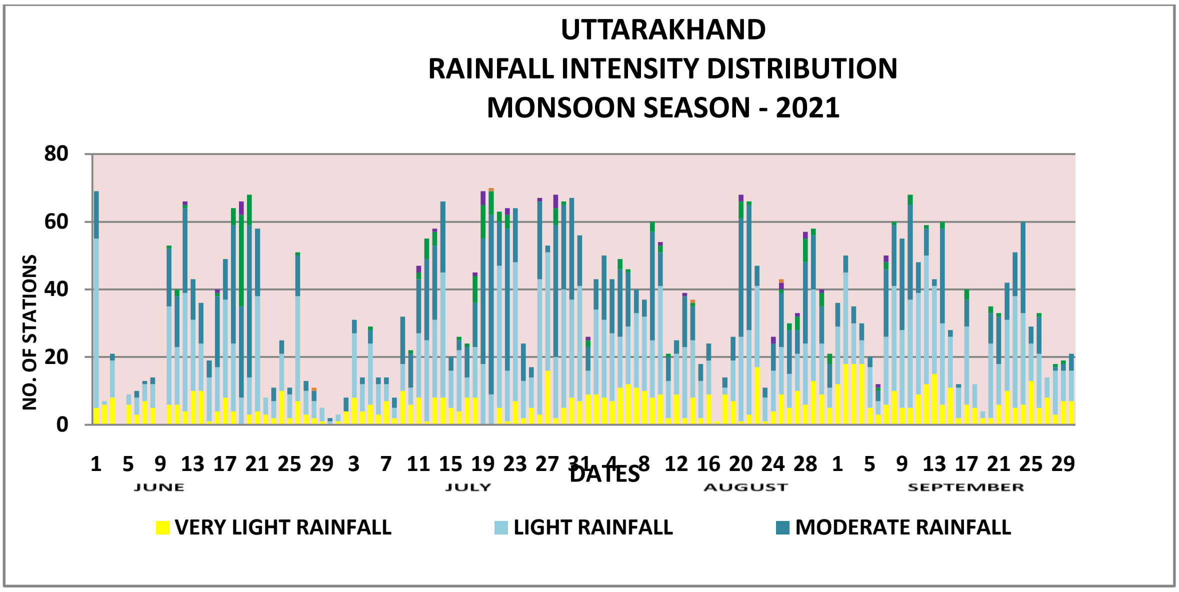


TABLE 3.1.7.1: MONTHLY DISTRIBUTION OF RAINFALL OVER THE STATE:

Met. Sub-division/ State	Month	Actual Rainfall (in mm)	Normal or Long period average(LPA) (in mm)	Departure from normal (in %)
Uttarakhand	June-2021	262.9	177.8	48
	July- 2021	371.6	407.7	-9
	August- 2021	307.6	397.7	-23
	September-2021	214.0	193.7	10

3.1.8.1: Highlight of Rajasthan

- Therainfallduringmonsoonseason(June-September,2021)overtheRajasthan state asawholewas 117% of its long period average (LPA) based on data of 1961-2010. **The rainfall received over the state was normal (Departure +17% of long periodaverage).**
- Seasonal rainfall occurred 116 % of its LPA over East Rajasthan and 120 % of its LPA over West Rajasthan.
- Monthly rainfall observed over the state was 106% of LPA in June, 85% of LPA in July, 86% of LPA in August and 176% of LPA in September. Highest monthly rainfall observed over the state as whole in the month of September (175.3mm) followed by July (130.8mm).
- Out of total 33 districts, 2 districts received large excess rainfall (Departure +60% or more), 10 districts received excess rainfall (Departure +20% to +59%), 19 districts received normal rainfall (Departure -19% to +19%) and 2

districts received deficient rainfall (Departure -20% to -59%) during the season.

3.1.8.2: RAINFALL DISTRIBUTION

The monthly rainfall during monsoon season (June to September) for the State as a whole and its two meteorological sub divisions are given in the table 1 with respective LPA values.

Table 3.1.8.1: Month wise distribution of rainfall during southwest monsoon 2021.

Month	Rajasthan as whole			East Rajasthan			West Rajasthan		
	Actuall Rainfall (mm)	Normal (mm)	Departure (%)	Actuall Rainfall (mm)	Normal (mm)	Departure (%)	Actuall Rainfall (mm)	Normal (mm)	Departure (%)
June	53.1	50.1	6	56.7	66.7	-15	50.2	36.9	36
July	130.8	153.5	-15	194	218.7	-11	80.7	101.7	-21
August	126.1	147.3	-14	236.7	221.9	7	38.3	88	-56
September	175.3	63.6	176	209.3	94.9	121	148.4	38.8	283

Table 3.1.8.2: Month wise highestone day rainfall during southwest monsoon 2021

Month	Station	District	Highest 24 hrs Rainfall (mm)	Observed Date
June	Banswara	Banswara	121	04/06/2021
July	Sahabad	Baran	304	31/07/2021
August	Sahabad	Baran	255	03/08/2021
September	Shrimadhopur	Sikar	153	23/09/2021

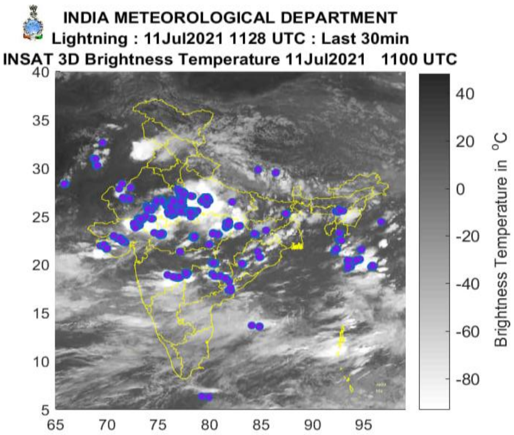
3.1.8.3:Extremely Heavy Rainfall Over South-East Rajasthan (31 July-05 August, 2021)

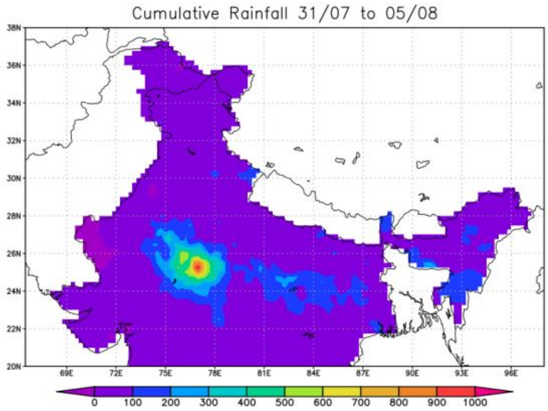
Under the influence of two low pressure systems, heavy to very heavy rainfall with isolated extremely heavy rainfall observed over the parts of South-East Rajasthan during 31st July to 5thAugust, 2021. Baran, Kota, Jhalawar and Sawaimadhopur districts of South-East Rajasthan adversely affected by consecutive four-five days extremely heavy rainfall and leads to the flash flood situation over the region.

Higher Moisture Flux Convergence (MFC) zone more than $200 \times 10^{-5}\ \mathrm{Kg\ m^{-2}}$ developed in association with low pressure system and shifted slowly west northwestward direction during 31st July to 02nd August. The system remained practically stationary during subsequent three days over SE Rajasthan and adjoining Madhya Pradesh. Two strong divergence zones were located separately over both the low pressure systems during 31st July and 01st August. Both the divergent fields merged into single zone on 2nd August. Merging of both diverging zones results enhanced upper air divergence upto$40 \times 10^{-6}\mathrm{sec}^{-1}$ over the region. The presence of anticyclonic circulation in upper level results slow movement of low pressure system and persisted for about two consecutive day's results extremely heavy rainfall over the same region.

3.1.8.4: Amer Fort, Jaipur Lightning Case 11th July, 2021

Under the influence of weak monsoon and stagnation conditions, reduced rainfall activity observed in the onset phase of monsoon between 28th June and 10th July in Rajasthan. By strengthening of lower lever easterly winds from 10th July onwards over the region results enhanced rainfall associated with thunderstorm and lightning from 11th July onwards. Around 40 people were gathered at two watchtowers near Amer Fort in Jaipur on 11th July evening hours. Lightning struck over a watchtower causes 12 numbers of causality and around 15 seriously injured as per local newspaper and state authorities.





3.1.9.1: Highlights of Monsoon Season 2021 of Uttar Pradesh

1. Southwest monsoon advanced into Uttar Pradesh on 13th June and covered most parts of east Uttar Pradesh and some parts of west Uttar Pradesh (districts adjoining Uttarakhand). On 18th June, it further advanced to cover the whole of east UP and some more parts of west UP on 11thJuly. Monsoon further progress and covered the whole of Uttar Pradesh on 13thJuly 2021. Progress of the Monsoon was stalled from 19th June to 10th July due to incursion and strengthening of mid-latitude westerlies over North India during the period.
2. The rainfall over the state as a whole during the monsoon season (June–September) was 95% of its long period average (LPA). Seasonal rainfall over East Uttar Pradesh and West Uttar Pradesh was 103% and 80% of respective LPAs. West Uttar Pradesh received deficient rainfall during the Monsoon season.
3. Out of the total 75 districts, 36 districts received Normal rainfall, 11 districts received Excess Rainfall, 2 districts received Large Excess rainfall and 26 districts received Deficient rainfall. No district received large Deficient rainfall.
4. Monthly rainfall over the state was 160% of LPA in June, 80% of LPA in July, 82% of LPA in August, and 101% of LPA in September. At the end of the monsoon season, rainfall was 5% less than its LPA.
5. Monthly rainfall departure over (i) East-UP was +88% from LPA in June, -28% from LPA in July, -1% from LPA in August, and 7% from LPA in September.

Monthly rainfall departure (ii) over West-UP was -30% from LPA in June, -7% from LPA in July, -43% from LPA in August, and -12% from LPA in September.

6. Of the total seasonal rainfall during the Monsoon season, 20% occurred in June, 28% in July, 29% in August, and 23% occurred in September.
7. In July, due to the absence of any major monsoon low pressure system over Bay of Bengal and the weak monsoon trough, Monsoon activity was weak over Uttar Pradesh. During the month, the monsoon trough lay to the north of its normal position or close to the foothills of the Himalayas on many days. This resulted in frequent and prolonged floods over areas of east Uttar Pradesh adjoining Bihar.
8. During August, the absence of formation of monsoon depression and less number of low-pressure areas (16-18 & 28-30 August) over the Bay of Bengal as against two monsoon depressions and two low-pressure areas caused deficient rainfall over West Uttar Pradesh. Most of the day's monsoon trough was located north of its normal position.
9. The monsoon withdrew rapidly from the whole of Uttar Pradesh within 2 days i.e., 08th and 09th October 2021.
10. During the season, 12 low-pressure systems (1 Cyclone, 1 Deep Depression, 1 Depression, 3 well-marked low-pressure areas & 6low-pressure areas) formed over the Indian sub-continent as against an average of 6 Depressions & 8 low-pressure areas. A deep depression formed during 12-15 September and cyclonic storm "GULAB" formed during 24-28 September.

3.1.9.2:The arrival of South West Monsoon over India and its advancement over Uttar Pradesh:

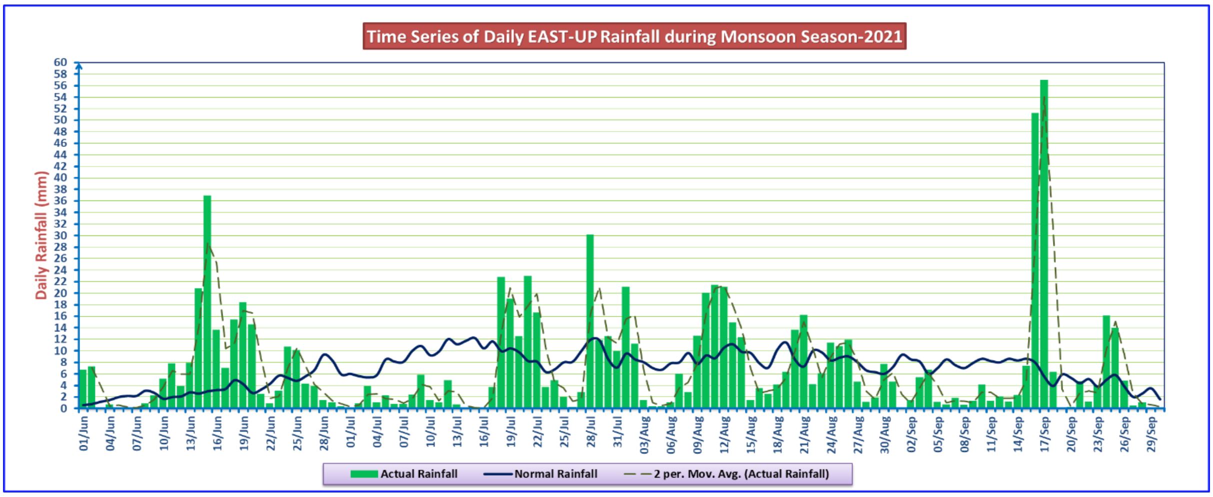
The onset of the South-west monsoon over Kerala occurred on 3rd June. It advanced into Uttar Pradesh on 13thJune 2021, due to the formation of a Low-Pressure area over Northwest Bay of Bengal & adjoining Odisha and Gangetic West Bengal coasts on 11thJune which gradually moved in the north-west direction and persistence of a cyclonic circulation over South Uttar Pradesh extending upto 1.5 km amsl from 10thto 12thJune 2021.

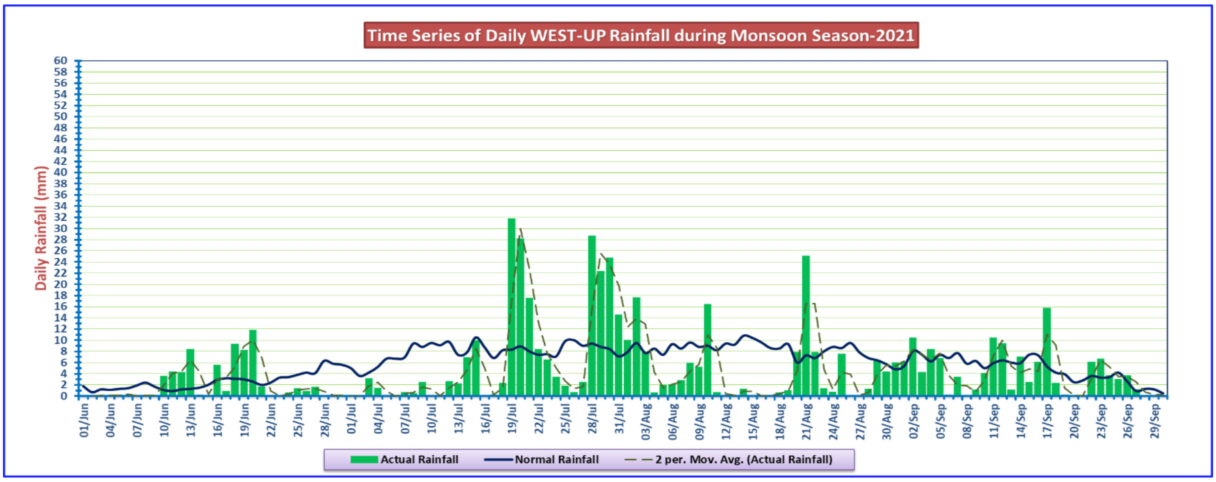
Due to Fairly Widespread Rainfall and Active monsoon conditions over East UP on 12thJune, SW monsoon advanced into most parts of East UP and some parts of West

UP on 13thJune. Northern limits of Monsoon passed through Hamirpur, Barabanki, Bareilly, and Saharanpur and covered all areas eastwards of these cities in Uttar Pradesh. This advancement was due to Vigorous monsoon activity and fairly widespread rainfall caused due to synoptic conditions i.e., Low-Pressure Area formed on 11thJune which became more marked and moved west-north-westwards during next two days, Cyclonic circulation over South UP, the trough from South Panjab to the center of LOPAR through Cyclonic circulation over South UP. The chief amount of rainfall realized on 13thJune was at Bansi-114mm (Siddharthnagar), Jalalpur-73mm (Ambedkarnagar), Muhammadi-69.4mm (kheri), Mehdawal-62mm (Santkabirnagar), Bareilly-71.2mm (Bareilly), Sahaswan-62mm (Badaun).

However, due to the approaching mid-latitude westerly winds, further progress of the monsoon over the remaining parts of northwest India and Uttar Pradesh was slow. On 18thJune, it further advanced to cover the whole of east UP and some more parts of West UP under the influence of cycir over south East UP after which there was a hiatus of about 23 days in further advancement of South West Monsoon. Northern Limit of monsoon further progressed on 11thand 12thJuly into West Uttar Pradesh and covered the entire country including the remaining parts of west UP on 13thJuly.

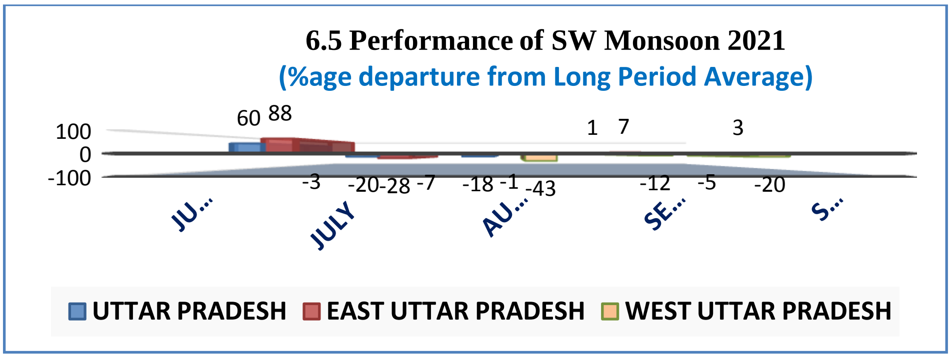
3.1.9.3 Daily Rainfall Time Series during South West Monsoon 2021



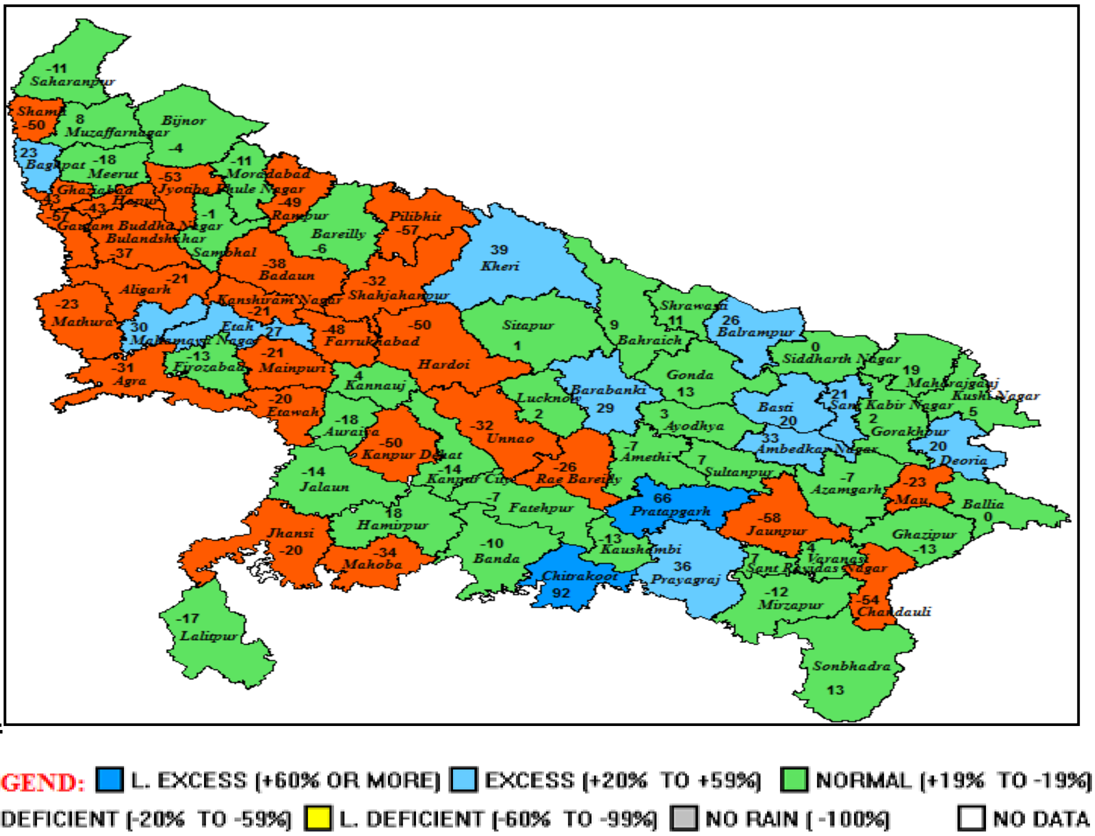


3.1.9.4:Monthly Rainfall

Sub-Division/State	Rainfall	**June-21**	**July-21**	**August-21**	**September-21**	**SW Monsoon-2021**
East Uttar Pradesh	Actual(mm)	203.8	203.5	260.1	200.1	867.5
	Normal(mm)	108.2	281.2	263.8	186.2	839.4
	Dep. (%)	88	-28	-1	7	3
West Uttar Pradesh	Actual(mm)	73.8	226.3	146	127.6	573.7
	Normal(mm)	76	243.9	256.7	144.7	721.3
	Dep. (%)	-3	-7	-43	-12	-20
Uttar Pradesh	Actual(mm)	151.5	212.6	214.2	170.9	749.2
	Normal(mm)	94.8	265.7	260.8	168.9	790.2
	Dep. (%)	60	-20	-18	1	-5



3.1.9.5: District wise Departure (%age) from Long Period Average for SW Monsoon Season -202



1

Actions Taken

- Warnings and press releases were issued by RWFC New Delhi with consultation with NWFC and all the MCs in theprint and electronic media.
- Warnings were also disseminated through website, SMS, Twitter, Facebook and WhatsApp.
- Impact Based Forecasts (IBF) were also issued during heavy rainfall events.
- Alerts were also issued every 3 hourly during heavy rainfall events and emailed to concerned ministries and meda groups.
- The warnings regarding heavy rainfall occurrence and the possibility of flooding was alsocommunicated on telephone and through email to the concerned officials of CWC and Delhi, UP, Rajasthan, Jammu & Kashmir, Himachal Pradesh, Uttarakhand, Punjab and Haryana State Govt. So that necessary steps could be initiated for ensuring the safety of life andproperty.

Chapter 3.2

DISASTROUS WEATHER EVENT OVERPARTS OF MADHYA PRADESH

Bhawna Kumariand M L Sahu, RMC Nagpur

3.2.1 Onset and Advance

The southwest monsoon set over Vidarbha on 9th June 2021. It set over Madhya Pradesh and Chhattisgarh on 11th June. It covered entire Vidarbha on 11th June, Chhattisgarh on 13th June and Madhya Pradesh on 19th June.

3.2.2 Seasonal cumulative rainfall

The seasonal cumulative rainfall distribution over West Madhya Pradesh was 15% more than long period average. 10 districts received excess rainfall, 19 districts received normal rainfall and 2 districts received deficient rainfall. East Madhya Pradesh received seasonal cumulative rainfall 15% less than LPA. 1 district received excess rainfall, 12 districts received normal rainfall and 7 districts received deficient rainfall. Vidarbha received seasonal cumulative rainfall of 3% more than LPA. 2 districts received excess rainfall and 9 districts received normal rainfall. Chhattisgarh received seasonal cumulative rainfall of 3% less than LPA. 1 district received excess rainfall, 22 districts received normal rainfall and 4 districts received deficient rainfall. The cumulative seasonal districtwise rainfall distribution during monsoon season over Madhya Pradesh, Vidarbha and Chhattisgarh is shown in Fig.3.2.1. The districtwise and sub divisional seasonal cumulative rainfall figures is also shown in Table 3.2.1

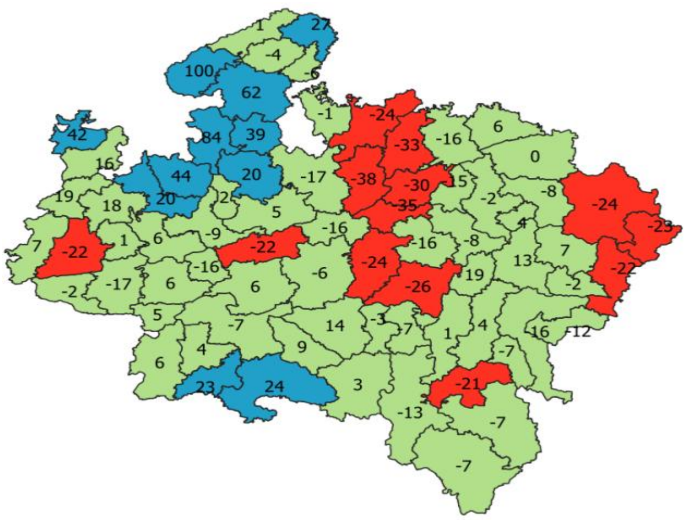


Fig.3.2.1: Districtwise Seasonal Rainfall Departure (%)

Table 3.2.1: District wise and sub divisional seasonal cumulative rainfall

WEST MADHYA PRADESH			
District	Actual (mm)	Normal (mm)	Dep(%)
Agar-Malwa	1224.2	812.1	51
Alirajpur	843.2	784.3	8
Ashoknagar	1182.3	852.1	39
Barwani	644.1	658.7	-2
Betul	1014.4	957.8	6
Bhind	834.1	657.7	27
Bhopal	979.8	962.4	2
Burhanpur	777.4	741.4	5
Datia	707.2	755.8	-6
Dewas	961.4	904.4	6
Dhar	650.5	835.9	-22
Guna	1633.2	888.1	84
Gwalior	718.2	747.9	-4
Harda	875.9	1042.1	-16
Hoshangabad	1025.9	1308.7	-22
Indore	836.6	827	1
Jhabua	829	774.7	7
Khandwa	837.5	790.9	6
Khargone	590.7	714.4	-17
Mandsaur	914.6	786.5	16
Morena	658.2	651.5	1
Neemuch	1056.3	742.3	42
Raisen	1123.6	1074.9	5
Rajgarh	1195.8	833.2	44
Ratlam	1035.1	867.5	19
Sehore	944.7	1043.3	-9
Shajapur	1065.1	886.7	20
Sheopur	1343.8	670.7	100
Shivpuri	1262.5	779.8	62
Ujjain	999.6	844.3	18
Vidisha	1181.8	982.2	20
Subdivision	**984.8**	**857.7**	**15**

EAST MADHYA PRADESH			
District	Actual (mm)	Normal (mm)	Dep(%)
Anuppur	1146.3	1099.6	4
Balaghat	985.5	1323	-26
Chhatarpur	719.4	947.5	-24
Chindwara	938.7	1001.3	-6
Damoh	644.8	1046.3	-38
Dindori	1088.4	1182	-8
Jabalpur	718.9	1111.2	-35
Katni	708.2	1011.9	-30
Mandla	1015.7	1210.7	-16
Narsinghpur	882.4	1046.6	-16
Panna	730.5	1087.4	-33
Rewa	1008.7	950.7	6
Sagar	896.1	1080.2	-17
Satna	799.3	949.2	-16
Seoni	784.2	1027	-24
Shahdol	971.7	989.5	-2
Sidhi	992.2	987.5	0
Singrauli	1257.9	837	50
Tikamgarh	878.9	889.2	-1
Umaria	908.9	1075	-15
Subdivision	**893.7**	**1048.4**	**-15**
Madhya Pradesh	**945.2**	**940.6**	**0**

VIDARBHA			
District	Actual (mm)	Normal (mm)	Dep(%)
Akola	723.4	693.8	4
Amraoti	799.3	862	-7
Bhandara	1117.7	1157	-3
Buldhana	699.9	659.4	6
Chandrapur	1112.3	1083.9	3
Gadchiroli	1087.2	1254.2	-13
Gondia	1129.6	1220.2	-7
Nagpur	1049.6	920.4	14
Wardha	957.1	874.5	9
Washim	974.4	789	23
Yeotmal	1000.9	805	24
Subdivision	**968.4**	**943.1**	**3**

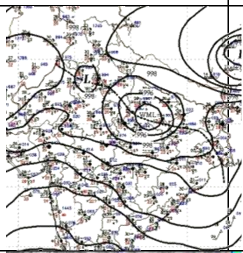
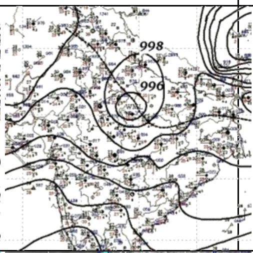
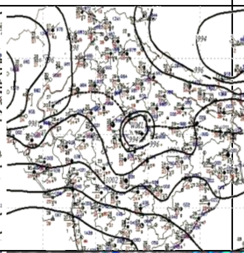
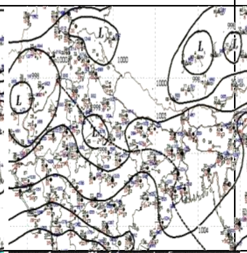
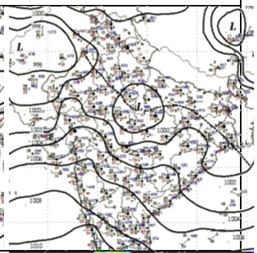
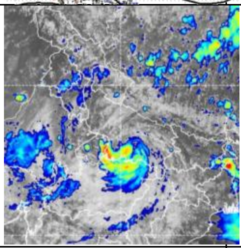
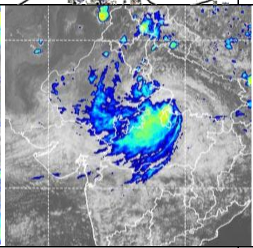
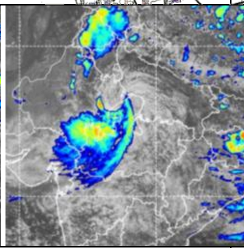
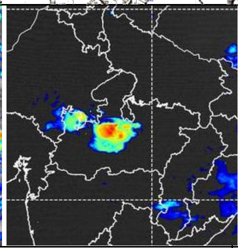
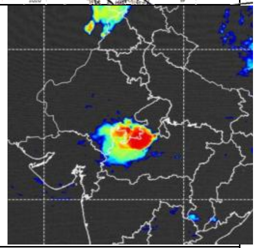
CHHATTISGARH			
District	Actual (mm)	Normal (mm)	Dep(%)
Balod	930.6	1013.5	-8
Baloda Bazar	965	946.1	2
Balrampur	1058.1	1165.6	-9
Bastar	1093.9	1171	-7
Bemetara	1177.2	1008.9	17
Bijapur	1216.5	1323.4	-8
Bilaspur	1231.1	1090.8	13
Dantewada	1203.9	1290.2	-7
Dhamtari	956.5	1031.3	-7
Durg	1024.5	984	4
Gariaband	1060.3	1079.1	-2
Janjgir	1150.8	1174.3	-2
Jashpur	1081.3	1405.7	-23
Kabirdham	1024.8	858.5	19
Kanker	1015.3	1291.4	-21
Kondagaon	1122.2	1174.1	-4
Korba	1399.5	1310.5	7
Koriya	1036.5	1132.1	-8
Mahasamund	921.7	1048.3	-12
Mungeli	1122.3	967.7	16
Narayanpur	1290.2	1202.4	7
Raigarh	934.6	1202.7	-22
Raipur	879.3	1051.5	-16
Rajnandgaon	982.4	976.8	1
Sukma	1564.7	1124	39
Surajpur	1265.6	1116.6	13
Surguja	926.7	1223.2	-24
Subdivision	**1107.7**	**1142.1**	**-3**

3.2.2 Case study of Heavy Rainfall spell over Madhya Pradesh during 1st to 7th August 2021

A low pressure area developed over North Bay of Bengal and neighborhood on 27th morning and moved in west-north-westward direction during subsequent 4 days which resulted in heavy rainfall over parts of Madhya Pradesh during 1st to 6th August 2021. The surface chart from 1st to 5th August shown in Figure.3.2.2 indicates the movement of well-marked low pressure area from southeast Uttar Pradesh and adjoining area which subsequently moved towards north Madhya

Pradesh and neighborhood. The system weakened into a low pressure area on 4th August.

Fig 3.2.2: Surface charts and IR Satellite imagery

01.08.2021	02.08.2021	03.08.2021	04.08.2021	05.08.2021
				
				
A Well Marked Low Pressure Area was lying over southeast Uttar Pradesh & neighbourhood with associated cyclonic circulation extending upto 7.6 km above mean sea level.	The Well Marked Low Pressure Area lay over southwest Uttar Pradesh & adjoining northwest Madhya Pradesh. The associated cyclonic circulation extendedupto 7.6 km above mean sea level.	The Well Marked Low Pressure Area was lying over southwest Uttar Pradesh & adjoining northwest Madhya Pradesh. The associated cyclonic circulation extends upto 7.6 km above mean sea level.	The Low Pressure Area lay over northwest Madhya Pradesh & neighbourhood. The associated cyclonic circulation now extends upto 5.8 km above mean sea level.	The Low Pressure Area over northwest Madhya Pradesh & neighbourhood lay over central parts of north Madhya Pradesh & neighbourhood. The associated cyclonic circulation extends upto 5.8 km above mean sea level.

On 6th August the Low Pressure Area was lying over the same region. On 7th August the Low Pressure Area moved away towards northern parts of East Madhya Pradesh & neighborhood with associated cyclonic circulation extending upto 4.5 km above mean sea level. Above system resulted in heavy to very heavy and also extremely heavy rainfall over parts of North and Central Madhya Pradesh. Parts of West Madhya Pradesh were most affected. The heavy rainfall received by various stations in East Madhya Pradesh is listed in Table 3.2.2. Prithvipur in Tikamgarh district received extremely heavy rainfall on 1st August (reported on 2nd August).

Table 3.2.2: Heavy Rainfall over East Madhya Pradesh (in mm)

01.08.2021				02.08.2021	
District: Rewa		District: Sidhi		District: Rewa	
Gudh	85	Kusmi	86.2	Semariya	75
Hanumana	155.4	Rampur	120	Sirmaur	65
Huzur	122.4	Sidhi	71.2	District: Tikamgarh	
Jawa	155	Sihawal	90.2	Baldevgarh	96
Mangawan	90	District: Singrauli		Jatara	89
Mauganj	100	Chitrangi	148.4	Niwari	175
Naigarhi	140	Devser	70	Orchha	170
Raipur	96	Sarai	106.4	Palera	110
Rewa-	135.4	Singrauli-	130.4	Prithvipur	210
Semariya	93	03.08.2021		Tikamgarh-	91
Teonthar	105	District: Tikamgarh			
District: Satna		Orchha	160		
Majhgaon	73.4	Prithvipur	80		
Satna	76				
Sohawal	90.3				

The heavy rainfall received by various stations in West Madhya Pradesh is listed in Table 3.2.3. Heavy rain was reported at isolated places over Guna and Sheopur on 1st August. Extremely heavy rainfall was reported by Bairad in Shivpuri district on 2nd August. Many stations reported heavy to very heavy rainfall in Shivpuri district. On 3rd August many stations in Shivpuri districts received extremely heavy rainfall, highest amount of 470 mm was received by Shivpuri station followed by Pichhore with 417 mm. Isolated places in Sheopur and Guna also received extremely heavy rainfall. As the system was lying over southwest Uttar Pradesh and adjoining areas of Madhya Pradesh, the rainfall was concentrated over Northern parts of West Madhya Pradesh. Heavy to very heavy rainfall was reported from 4th to 7th August also, but the impact of accumulated rainfall from 1st to 3rd August was comparatively higher. The districts which were mostly affected were Guna, Sheopur and Shivpuri. The cumulative rainfall for different stations in these districts is shown in figure 3.2.3. The cumulative rainfall from 1st to 7th August over Bamori station of guna district was 1043.6 mm followed by Raghoharh with 681 mm and so on. The cumulative rainfall from 1st to 4th August over Karhal of Sheopur district wad 596 mm followed by Sheopur with 558 mm and so on. Three days cumulative rainfall from 2nd to 4th August over Pohri station of Shivpuri district was 744 mm followed by Shivpuri with 649 mm and so on.

Table 3.2.3: Heavy Rainfall over West Madhya Pradesh (in mm)

01.08.2021	
District: Guna	
Kumbhraj	75
Raghogarh	88
District: Sheopur	
Badoda	80
Karhal	75
Sheopur-	73
Veerpur	75
02.08.2021	
District: Ashoknagar	
Chanderi	125
Isagarh	101
District: Guna	
Bamori	138
Guna-	106.8
Raghogarh	90
District: Shivpuri	
Badarwas	135
Bairad	286
Karera	95
Khaniyadana	87
Kolaras	125
Narwar	163
Pichhore	73.1
Pohri	195
Shivpuri	117
District: Morena	
Alipur(Jaura)	66
Sabalgarh	120
District: Rajgarh	
Biaora	64.6
Khilchipur	65.4
Narsingarh	72
Zirapur	71
District: Sheopur	
Badoda	83
Karhal	126
Sheopur	115
Veerpur	88
Vijaypur (Adp)	160.5

03.08.2021	
District: Sheopur	
Badoda	180
Karhal	190
Sheopur	250
Veerpur	215
Vijaypur	175
District: Guna	
Aron	112
Bamori	271
Guna	143.6
Kumbhraj	83
Raghogarh	158
District: Shivpuri	
Badarwas	192
Bairad	227
Karera	272
Khaniyadana	327
Kolaras	320
Narwar	206
Pichhore	417
Pohri	384
Shivpuri	470
04.08.2021	
District: Guna	
Bamori	173
Chachoda	65
Guna	78.1
Raghogarh	68
District: Sheopur	
Badoda	110
Karhal	205
Sheopur	120
District: Shivpuri	
Badarwas	78
Kolaras	65
Pohri	165
05.08.2021	
District: Guna	
Chachoda	115
Kumbhraj	93
District: Vidisha	
Ganjbasoda	84.6
Gyaraspur	77
Lateri	85
Nateran	94
Pathari	76

06.08.2021	
District: Guna	
Aron	100.3
Bamori	128
Chachoda	174
Guna-	65
Kumbhraj	153
Raghogarh	160
District: Vidisha	
Kurwai	72
Lateri	117
Nateran	72
Shamshabad	150.1
Sironj	168
District: Rajgarh	
Biaora	105.4
Khilchipur	68.5
Narsingarh	65
Rajgarh	85.2
Sarangpur	75.2
Zirapur	80
District: Ashoknagar	
Ashoknagar	79
Isagarh	71
District: Sheopur	
Karhal	73
07.08.2021	
District: Guna	
Aron	87
Bamori	209.4
Guna	164.1
Kumbhraj	93
District: Mandsaur	
Bhanpura	96.4
Garoth	88.8
Shamgarh	64.6
District: Vidisha	
Gyaraspur	81
Kurwai	124.4

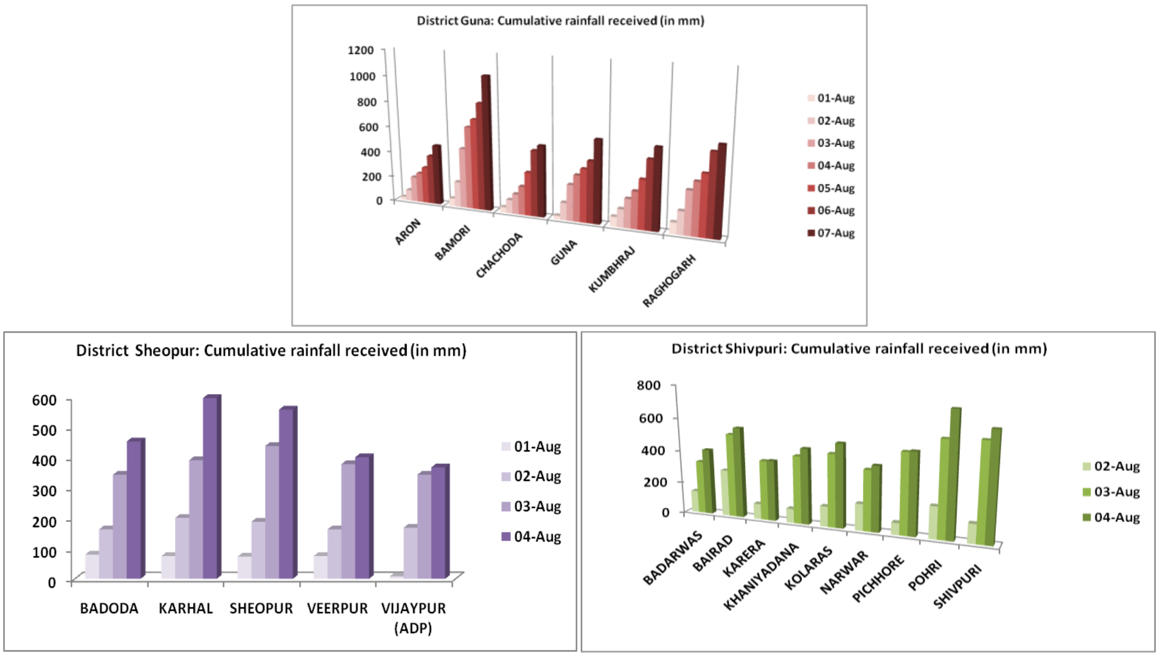


Fig. 3.2.3: Cumulative rainfall over Guna, Sheopur and Shivpuri

Since the Well Maked Low moved westward from UP to MP so the maximum convergence zone was in the SW sector of system in NW Madhya Pradesh. The movement of system was slow so rainfall occurred for longer period. The RADAR observation in Figure 3.2.4 also indicates that the cloud mass was concentrated over the northwestern parts of west Madhya Pradesh where these three most affected districts, i.e. Guna, Sheopur and Shivpuri, are situated.

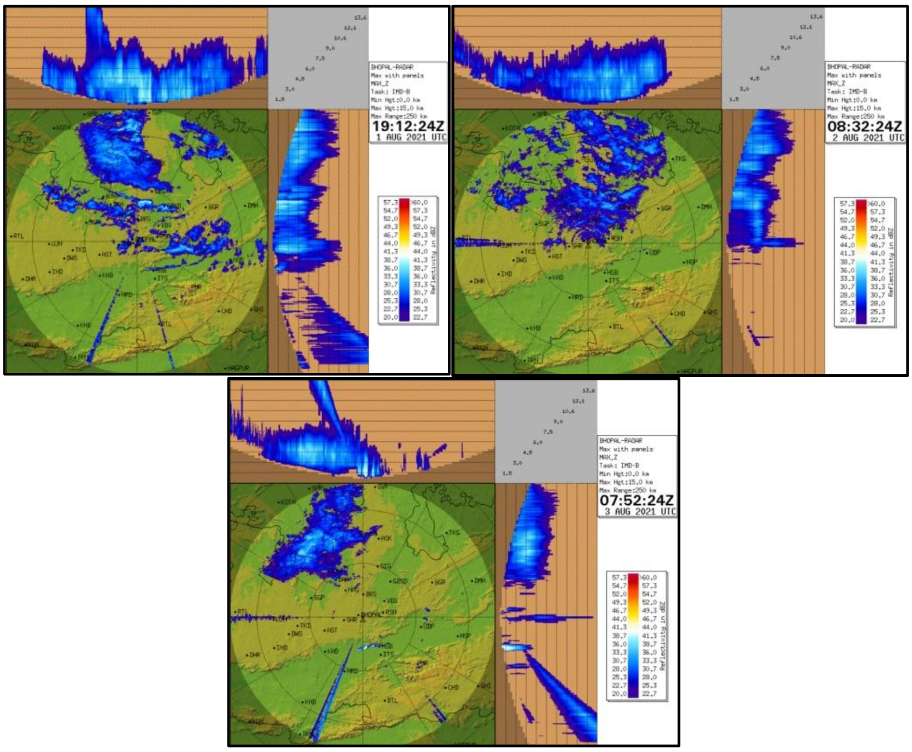


Figure 3.2.4: Bhopal RADAR images for 1st, 2nd and 3rd August 2021

3.2.3 Flood over Madhya Pradesh

The cumulative rainfall over the northern districts of west Madhya Pradesh resulted in heavy flood situation over many low lying areas. As per the news reports 1,225 villages in Shivpuri, Sheopur, Datia, Gwalior, Guna, Bhind and Morena districts were affected. Air Force, Army and NDRF and SDRF teams were deployed for rescue operations.

Infrastructure facilities like telephone tower, mobile network, electricity, roads and bridges were severely damaged as per the reports. Few fatalities were also reported by the media.

Chapter 3.3

SOUTH WEST MONSOON 2021 OVER MAHARASHTRA, GOA AND GUJARAT

Monsoon has always been challenging over West coast of India. With typical weather systems very heavy to extremely heavy rainfall events are very common over the region. Regional Meteorological Centre, Mumbai is one of the six Regional Centres of India Meteorological Department responsible for monitoring and providing weather services to the states of Maharashtra, Goa, and Gujarat (excluding Vidarbha region of Maharashtra State). This chapter presents the analysis of some major weather events over Maharashtra, Gujarat and Goa during monsoon 2021.

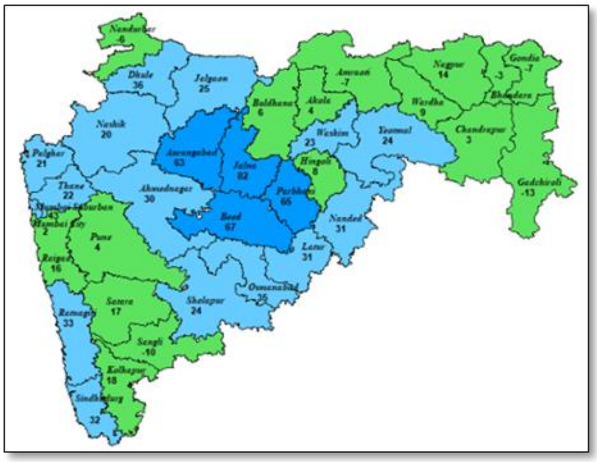
SOUTH WEST MONSOON 2021 OVER MAHARAHSTRA

Dr. Jayanta Sarkar, Dr.Sushma Nair, Nitha.T.S, Shambu Ravindren,

Dr. Jimsy Poulose

3.3.1 Introduction

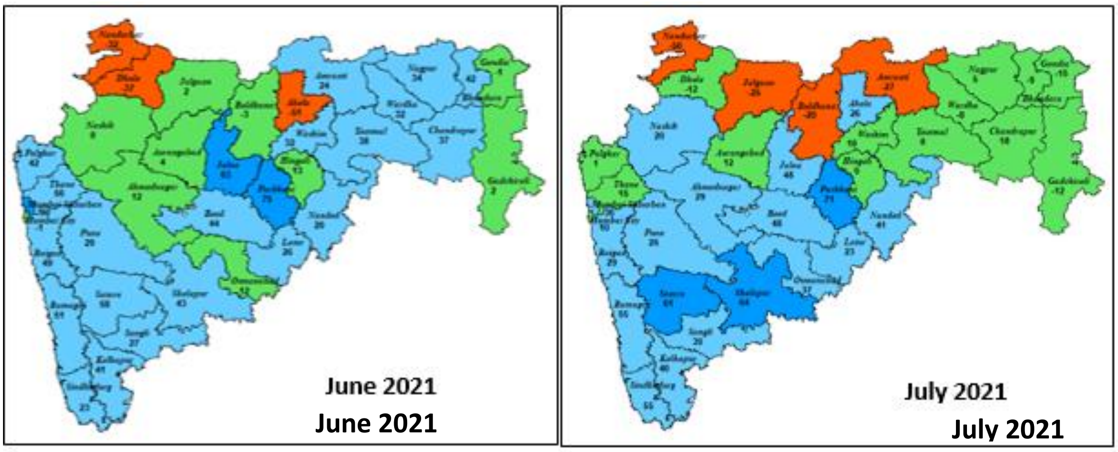
Maharashtra receives most of its annual rainfall in the South West monsoon season (June to September). The Southwest Monsoon advanced over Maharashtra on 5th June 2021. The onset of monsoon was declared in Mumbai on 9th June 2021, two days before its normal onset. The normal for monsoon rainfall over the state is 1004.2 mm. The seasonal (June to September) rainfall over Maharashtra for 2021 was 1194.3 mm with a departure of 19% from its long term value. The rainfall district wise and subdivision wise rainfall distribution for the 36 districts and the four subdivisions is illustrated for the season as a whole and for the individual monsoon months. Out of the 36 districts the seasonal rainfall was in Large Excess (60%) in 4 districts (all in Marathwada), Excess (20% to 59%) in 15 districts and Normal (19% to -19%) in 16 districts. However the district wise monsoon rainfall showed distinct and contrasting variations in the individual months. The subdivision wise distribution of rainfall is represented graphically for the individual months and for the season as a whole.



LEGEND: L. EXCESS (+60% OR MORE) EXCESS (+20% TO +59%) NORMAL (+19% TO -19%)
DEFICIENT (-20% TO -59%) L. DEFICIENT (-60% TO -99%) NO RAIN (-100%) NO DATA

Fig (3.3.1) Percentage departure of rainfall over Maharashtra during monsoon (June – September) 2021

Rainfall was normal to above normal in most of the districts the Month of June, and deficient over 3 districts. In the month of July also most of the districts of the state recorded normal to above normal rainfall, however 4 districts received deficient rainfall. However, in the month of August 2022 most of the districts received deficient rainfall, with districts of Pune and Satara recording a large deficient. 9 districts had normal to above normal rainfall. However, the month of September was the rainiest month over the state with most of the districts receiving a large excess and 2 districts each receiving excess and normal rainfall. One district however received deficient rainfall.



LEGEND: L. EXCESS (+60% OR MORE) EXCESS (+20% TO +59%) NORMAL (+19% TO -19%)
DEFICIENT (-20% TO -59%) L. DEFICIENT (-60% TO -99%) NO RAIN (-100%) NO DATA

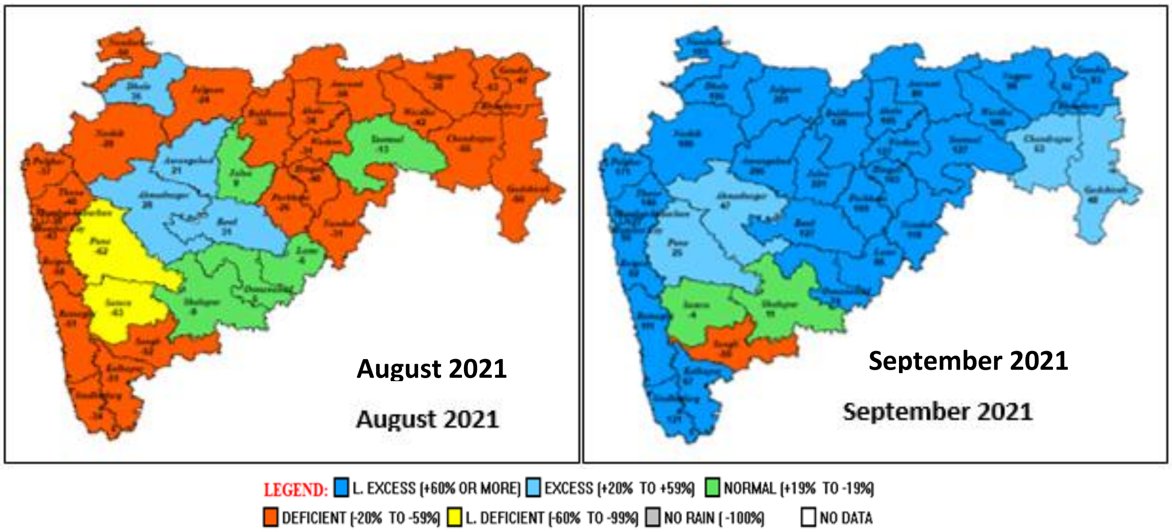


Fig (3.3.2) Percentage departure of rainfall over Maharashtra during monsoon (June – September) 2021

In June and July all the subdivisions received normal to above normal rainfall, while the rainfall distribution was normal to below normal in August over the different subdivisions of Maharashtra. However, in September at the subdivision level the rainfall departure from normal was in large excess over all the four subdivisions. The South West Monsoon withdrew from Mumbai on October 14th 2021, a 4 day delay as against the normal withdrawal date of 10th October. It withdrew entirely from the state on 16th October 2021.

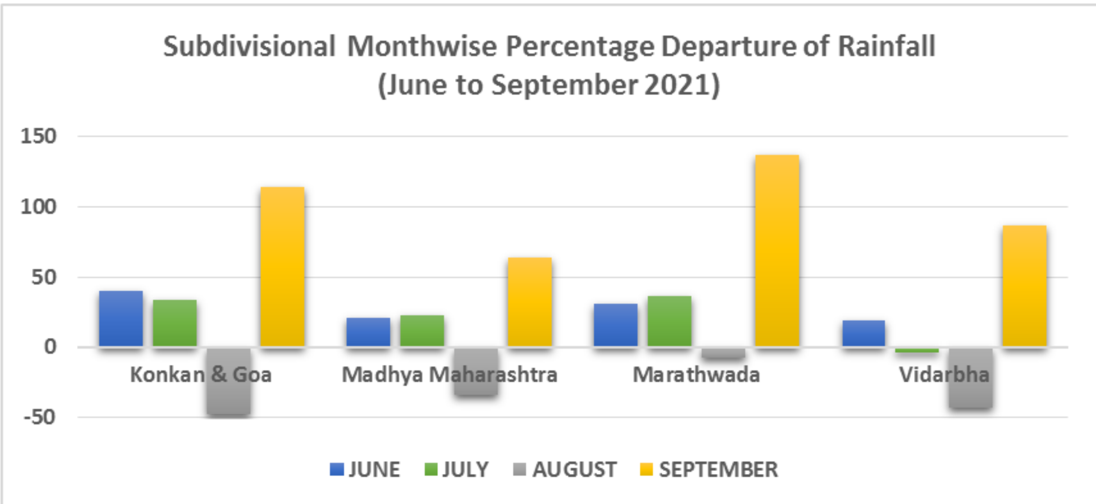


Fig (3.3.3) Monthly Percentage departure of rainfall over Maharashtra during monsoon (June – September) 2021

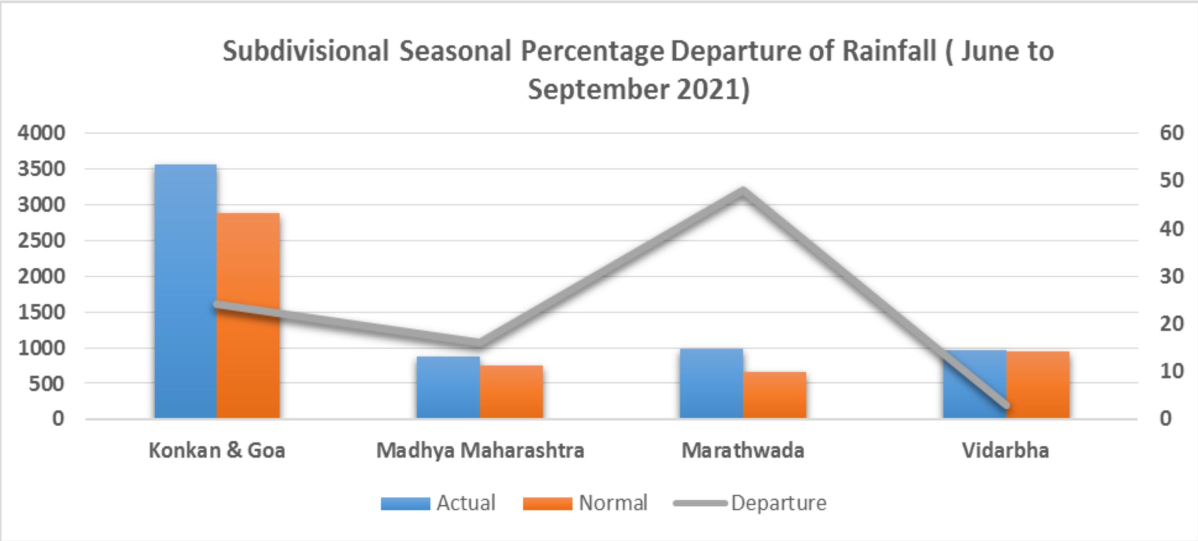


Fig (3.3.4) Seasonal Percentage departure of rainfall over Maharashtra during monsoon (June – September) 2021

Rainfall over Maharashtra shows significant spatial and temporal variability. It experiences extremes of rainfall ranging from 600 cm over the Ghats to less than 60 cm in Madhya Maharashtra. Like every year, monsoon 2021 also made its footprints over the region with its heavy rainfall episodes associated with typical synoptic conditions. Of the various heavy rainfall events, Multiday spell of extremely heavy rainfall over Konkan and Madhya Maharashtra during 18th July to 24th July 2021 which led to flooding over the region is discussed here.

3.3.2 Multiday spell of extremely heavy rainfall over Konkan and Madhya Maharashtra during 18th July to 28th July 2021

Event: One of the major events during Monsoon 2021 was the multiday spell of very heavy to extremely heavy rainfall over parts of Konkan and South Madhya Maharashtra during 18th to 24th July 2021, which led to severe flooding and landslides over the region. The most affected regions were the districts of Raigad, Ratnagiri, Sindudurg, Satara, Sangli and Kolhapur. Due to heavy rains, more than 1,020 villages are affected in these districts. Over 375,000 people were evacuated from several parts of these districts. Initial estimates of the state indicated over

2 lakh hectares of crops were damaged in the flood over the region. Various infrastructural facilities were impacted and damaged.

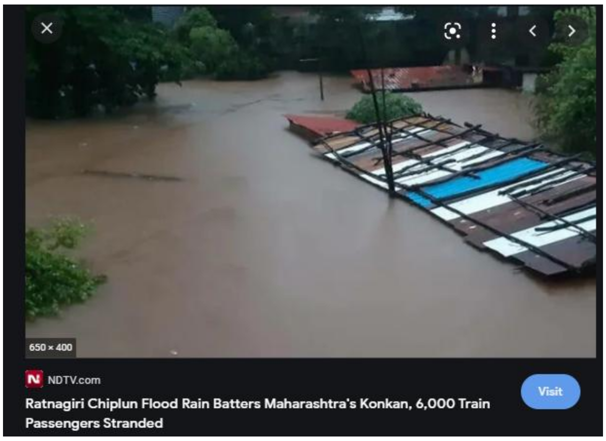


Fig (3.3.5)Media reports about the flooding events over Konkan and Madhya Maharahstra

3.3.3 Weather Systems that led to the event:

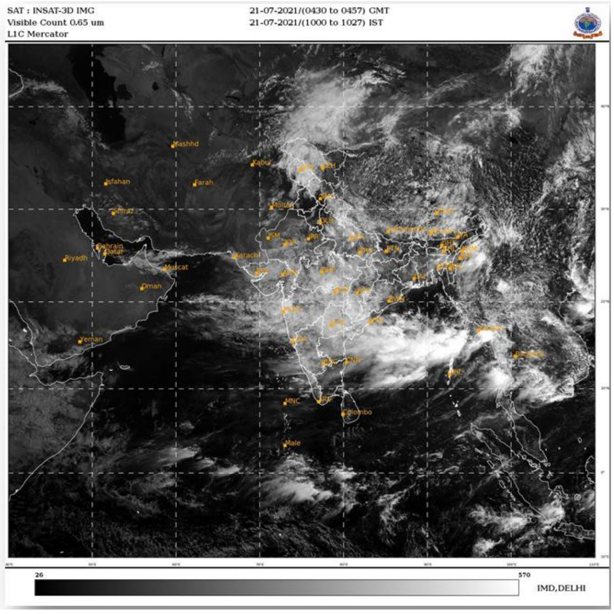
The persistent intense rainfall activity over the region was in association with an active spell of monsoon which started over Maharashtra from 16th July 2021 and resulted in flooding and landslides in some parts of north Konkan This heavy to very heavy rainfall activity continued over the coastal belt and adjoining ghat areas of

Madhya Maharashtra in association with the typical synoptic situations associated with the formation of low pressure area over Bay of Bengal by 21st July 2021. The chief synoptic situations present during the event is discussed below:

- In association with the formation of **low pressure area over Bay of Bengal**, the monsoon currents over the west coast strengthened from 18th July 2021. Low Pressure Area formed over North Bay of Bengal neighbourhood on 21st July 2021. It concentrated into a well-marked low pressure area over Northwest Bay of Bengal off north Odisha- West Bengal coasts on 23rd July. It moved westward across Jharkhand and adjoining areas of North Chhattisgarh and Odisha on 24th July and further moved further inland across North east Madhya Pradesh as a low pressure area and became less marked on 26th July. This movement of low pressure system across central India, resulted in enhancement of rainfall over west coast and in the ghat areas of Madhya Maharashtra with heavy to very heavy rainfall (~12 to 20 cm) and extremely heavy rainfall (more than 20 cm) events for more than a week period over these places, resulting in severe flood situations.
- An **off – shore trough** at mean sea level persisted along the west coast from 15th July. It ran from North Kerala coast to Maharashtra from 16th July and persisted over the same area on 18th, 19th and 20th July. It further extended to south Gujarat coast from 21st July 2021.It persisted along the west coast till 25th July.

- Another favorable weather system was the presence of **East-West Shear Zone** oriented along Lat 17^{0} N from 18th July observed at mid and upper tropospheric levels during the period

  The combined influence of these synoptic situations moisture laden westerly strength increased and provided all supporting dynamical conditions across the region leading to very high number of extreme rainfall events with longer spell period.



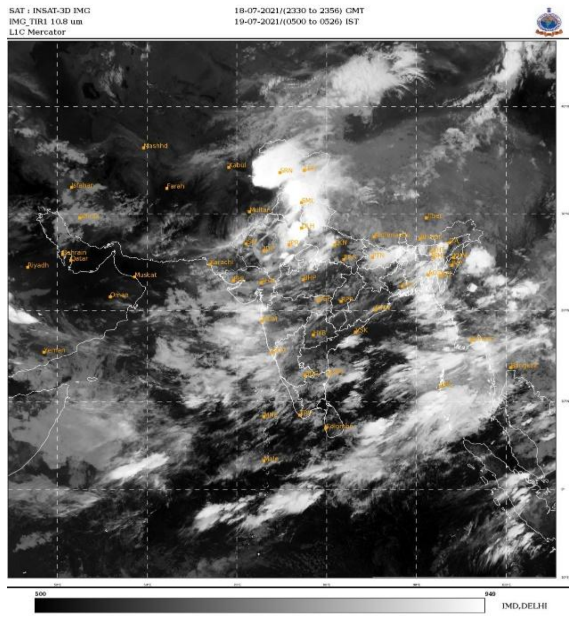


Fig (3.3.6): Satellite imageries of 18th and 21st July 2021 indicating active monsoon conditions over west coast.

3.3.4 Significant rainfall realized :

Entire belt of Konkan and ghat areas of Madhya Maharashtra received moderate to heavy rainfall with heavy to very heavy rainfall at many places and isolated extremely heavy falls. Significant rainfall (24 hour accumulated) received over the districts of Konkan and Madhya Maharashtra is shown in the table. Widespread moderate to heavy rain occurred over all the districts of Konkan and adjoining ghat areas of central and south Madhya Maharashtra during the period 18-23 July 2021.

DISTRICT:PALGHAR	16-Jul	17-Jul	18-Jul	19-Jul	20-Jul	21-Jul	22-Jul	23-Jul
DAHANU - IMD OBSY	25.2	9.8	174.0	7.5	8.6	32.3	16.2	2.4
JAWHAR	65.0	31.0	43.0	192.0	112.0	117.0	434.0	24.0
MOKHEDA - FMO	10.2	13.6	46.6	210.8	58.4	106.2	289.4	12.0
PALGHAR_AGRI	34.4	17.4	236.6	31.0	4.0	56.4	77.4	32.6
TALASARI	8.0	13.0	125.0	82.0			51.0	4.0
VASAI	31.0	96.0	186.0	42.0	45.0	25.0	48.0	14.0
VIKRAMGAD	12.0	23.0	37.0	215.0	70.0	130.0	231.0	14.0
WADA	4.0	4.0	76.0	109.0	27.0	114.0	418.0	17.0
DISTRICT: MUMBAI CITY								
COLABA - IMD OBSY	12.8	14.6	196.8	42.6	35.4	8.0	96.6	12.8
Mahalaxmi_AWS	59.0	30.5	164.0	46.5	33.0	15.0	60.0	3.5
DISTRICT: MUMBAI SUBURBAN								
SANTACRUZ - IMD OBSY	253.3	31.2	234.9	70.4	38.4	23.9	57.7	19.4
DISTRICT: THANE								
AMBERNATH	8.0	20.0	87.0	153.6	253.0	43.3	112.0	30.4
BHIWANDI	12.0	48.0	50.0	155.0	300.0	65.0	142.0	15.0
KALYAN	11.0	14.0	66.0	180.0	368.0	54.0	189.0	21.0
MURBAD	2.0	5.0	19.0	56.0	71.0	31.0	226.0	13.0
SHAHAPUR	4.0	4.0	70.0	200.0	103.0	106.0	205.0	20.0
TBIA IMD PART TIME	51.0	53.2	213.6	285.2	164.8	35.8	103.0	24.2
THANE	34.0	105.0	180.0	210.0	159.0	39.0	132.0	24.0
ULHASNAGAR	14.0	29.0	67.0	200.0	288.0	57.0	122.0	25.0

DISTRICT: PUNE	16-Jul	17-Jul	18-Jul	19-Jul	20-Jul	21-Jul	22-Jul	23-Jul	24-Jul	25-Jul	26-Jul
AMBEGAON GHODEGAON	0.0	3.0	1.0	2.0	15.0	19.0	129.0	43.0	32.0	9.0	41.0
BARAMATI	0.0	4.0	0.6	0.0	0.2	0.0	3.0	0.0	1.0	0.0	0.4
BHOR	2.0	1.0	0.0	8.0	9.0	19.0	55.0	22.0	124.0	45.0	28.0
CHINCHWAD - ARG	2.5	0.5	2.5	11.0	23.0	16.5	35.5	10.0	64.5	9.0	10.0
DAUND	0.0	7.0	0.0	0.0	4.0	1.0	0.0	0.0	0.0	0.0	0.0
INDAPUR	3.2	0.0	4.2	0.0	2.2	0.0	3.8	0.0	0.0	0.0	0.0
JUNNAR	0.0	4.0	1.0	27.0	11.0	4.0	31.0	59.0	2.0	0.0	7.0
KHED RAJGURUNAGAR	0.0	2.0	0.0	1.0	24.0	8.0	25.0	7.0	8.0	3.0	7.0
LONAVALA_AGRI	14.4	28.4	79.1	167.1	149.1	71.4	313.1	295.3	125.0	67.3	57.0
NDA PUNE - ARG	0.0	0.5	1.0	11.0	32.5	9.0	40.0	23.5	73.5	23.0	22.5
PAUD MULSHI	7.0	2.0	6.0	19.0	55.0	40.0	112.0	155.0	145.0	30.0	35.0
PUNE CITY - IMD OBSY	1.3	3.1	0.5	11.7	11.7	4.3	17.4	5.6	80.3	6.5	9.7
PURANDAR SASVAD	0.0	0.0	2.0	0.0	3.0	5.0	10.0	0.0	32.0	2.0	5.0
SHIRUR GHODNADI	0.0	0.0	0.0	0.0	12.0	0.0	0.0	0.0	0.0	0.0	0.0
TALEGAON AWS	2.0	0.0	4.0	30.0	20.0	22.0	21.0	56.5	3.0	0.0	3.5
VADGAON MAVAL	4.0	4.4	15.0	27.0	41.0	28.4	106.0	66.4	121.4	14.6	31.6
VELHE	3.0	3.0	0.0	28.0	2.0	45.0	136.0	205.0	198.0	30.0	82.0

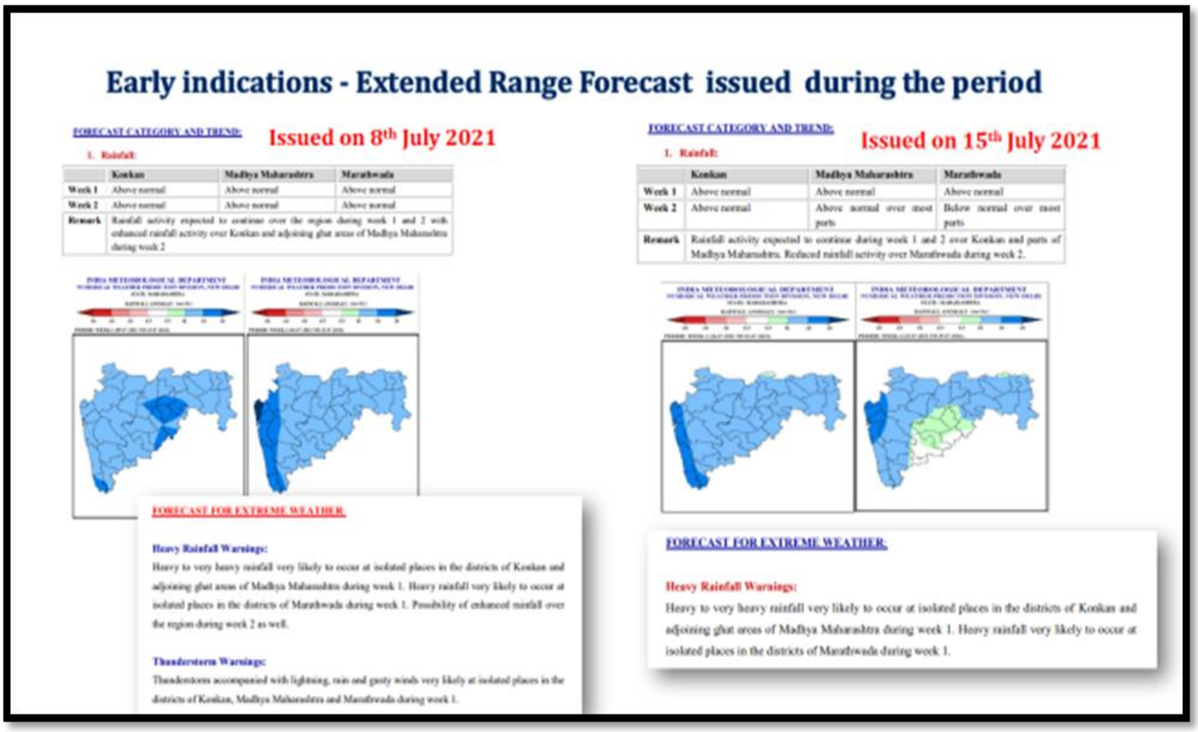
DISTRICT: SATARA	16-Jul	17-Jul	18-Jul	19-Jul	20-Jul	21-Jul	22-Jul	23-Jul	24-Jul	25-Jul	26-Jul
DAHIWADI MAN	0.0	0.0		0.0	2.0	1.0	9.0	0.0	7.0		0.0
JAVALI MEDHA	0.0	0.0	0.0	2.0	16.0	46.0	146.0	91.0	180.0	34.0	53.0
KARAD	6.0	1.0	11.0	6.0	11.0	11.0	85.0	21.0	124.0	4.0	14.0
KHANDALA BAVDA	0.0	0.0	1.0	1.2	5.2	2.0	23.2	1.0	69.0	9.8	2.8
MAHABALESHWAR- IMD O	61.8	47.0	78.4	97.8	109.8	164.0	480.0	594.4	321.0	186.7	154.2
PADEGAON_AGRI	0.0	0.0	0.0	0.0	0.0	0.0	9.4	0.0	25.0	6.6	3.2
PATAN	7.0			7.0	22.2	25.0	163.3	312.0	187.4		37.4
SATARA - IMD OBSY	1.8	0.5	3.3	4.7	4.7	25.7	92.7	17.6	172.3	19.9	20.7
WAI	2.0	0.0	0.0	4.0	7.0	14.0	140.0	28.0	164.0	27.0	22.0
DISTRICT: KOLHAPUR											
AJRA	18.0	4.0	5.0	48.0	22.0	25.0	82.0	399.0	85.0		22.0
CHANDGAD	40.0	16.0	5.0	43.0		48.0		280.0	118.0		
GADHINGLAJ	13.0	0.0	2.0	48.0	12.0	22.0	52.0	246.0	107.0	34.0	11.0
GAGANBAWADA	9.0	50.0	117.0	179.0	75.0	149.0	265.0	356.0	75.0	120.0	132.0
GARGOTI / BHUDARGAD	8.0	2.0	2.0	12.0	8.0	13.0	75.0	180.0	35.0	25.0	13.0
HATKANANGALE	1.0	2.0	4.0	11.0	6.0	12.0	55.0	81.0	117.0	3.0	7.0
KAGAL	4.0	3.0	4.0	32.0	7.0	24.0	93.0	178.0	222.0	6.0	15.0
KOLHAPUR/KARVIR IMD	5.6	2.4	1.9	29.2	9.1	36.3	103.5	146.8	181.0	4.4	15.7
PANHALA	21.0	15.0	13.0	30.0	26.0	50.0	148.0	275.0	210.0	30.0	34.0
RADHANAGARI	30.0	12.0	46.0	72.0	38.0	68.0	188.0	399.0	85.0	86.0	89.0
SHAHUWADI	6.0	12.0	20.0	30.0	32.0	61.0	78.0	231.0	135.0	66.0	56.0
SHIROL	0.0	0.0	15.0	13.0	3.0	15.0	30.0	22.0	60.0	0.0	0.0

DISTRICT: RAIGAD	16-Jul	17-Jul	18-Jul	19-Jul	20-Jul	21-Jul	22-Jul	23-Jul
ALIBAG - IMD Part Time	75.8	27.0	120.4	158.0	65.4	10.4	44.3	12.2
KARJAT_AGRI	11.8	42.4	74.2	194.6	189.2	80.2	321.8	152.6
KHALAPUR	21.0	25.0	113.0	195.0	183.0	52.0	202.0	77.0
MAHAD	53.0	34.0	68.0	89.0	94.0	91.0	207.0	
MANGAON	43.0	45.0	51.0	207.0	99.0	53.0	168.0	96.0
MATHERAN	13.4	35.2	138.4	268.4	255.7	113.5	331.4	152.0
MHASLA	87.0	75.0	113.0	159.0	53.0	46.0	87.0	60.0
MURUD	117.0	65.0	136.0	270.0	37.0	7.0	43.0	3.0
PANVEL_AGRI	13.2	57.0	182.0	284.2	182.2	48.0	137.6	53.4
PEN	28.0	53.0	168.0	180.0	187.0	29.0	146.0	45.0
POLADPUR	45.0	49.0	69.0	122.0	68.0	65.0	271.0	305.0
ROHA	82.0	57.0	184.0	202.0	153.0	37.0	129.0	44.0
SHRIWARDHAN	84.0	68.0	89.0	163.0	101.0	16.0	58.0	20.0
SUDHAGAD PALI	75.0	52.0	120.0	166.0	220.0	55.0	220.0	115.0
TALA	74.0	41.0	85.0	210.0	87.0	30.0	177.0	42.0
URAN	55.0	46.0	155.0	151.0	77.0	12.0	98.0	28.0
DISTRICT: RATNAGIRI								
CHIPLUN	72.0	85.0	64.0	73.0	126.0	104.0		
DAPOLI_AGRI	100.0	158.0	113.0	243.0	228.0	40.0	160.0	45.0
GUHAGARH	124.0	131.0	48.0	167.0	113.0	85.0	48.0	3.0
HARNAI IMD OBSY	100.4	12.0	70.8	190.4	153.2	25.6	60.8	
KHED	65.0	88.0	109.0	142.0	114.0	84.0	195.0	81.0
LANJA	162.0	55.0	103.0	205.0	60.0	145.0	220.0	70.0
MANDANGAD	90.0	81.0	76.0	89.0	89.0	73.0	165.0	115.0
RAJAPUR	111.0	45.0	136.0	118.0	106.0	135.0	139.0	103.0
RATNAGIRI - IMD OBSY	218.8	58.4	255.6	151.6	83.4	112.9	95.7	6.6
SANGAMESHWAR DEVRU	122.0	54.0	104.0	83.0	81.0	157.0	252.0	174.0
WAKWALI_AGRI	100.4	133.6	69.1	213.2	167.4	86.4	210.8	80.2
DISTRICT: SINDHUDURG								
DEVGAD	104.0	51.0	42.0	200.0	87.0	40.0	63.0	65.0
DODAMARG	89.0	28.0	14.0	119.0	40.0	56.0	75.0	184.0
KANKAVLI	113.0	58.0	33.0	240.0	87.0	82.0	77.0	185.0
KUDAL	169.0	40.0	50.0	144.0	50.0	37.0	50.0	126.0
MALVAN	303.0	49.0	48.0	190.0	44.0	11.0	29.0	27.0
MULDE_AGRI	142.4	38.4	55.8	127.4	49.8	32.1	32.4	135.0
RAMESHWAR_AGRI	107.6	46.8	57.8	232.2	55.4	72.4	79.8	39.0

Table(3.3.1): Rainfall (24 hour accumulated from 0830 hrs of the day 0830 hrs of next day) received over the districts of Konkan and Madhya Maharashtra

3.3.5 Forecasting and Severe Weather Warnings with Special Bulletins & Impact Based Forecast Guidance:

The rainfall event and its dynamics features were continuously monitored round the clock with Surface Weather Observatories, State Government/MCGM Rain-Gauge Network, Automated Weather Stations (AWS) network, Satellite and Doppler weather radar products. IMD mobilized all its resources along with Numerical Weather Models (IMD GFS, GEFS, NCUM – Regional / Global Models) to track the heavy rainfall events. The area of Konkan and adjoining Madhya Maharashtra were under constant monitoring. The first indications of likelihood of above normal rainfall accompanied with heavy rainfall over the region was indicated in the extended range forecast issued on 8th July 2021, two week prior to the event.



Fig(3.3.7): Extended range forecast issued on 8th and 15th July 2021 indicating likelihood of above normal activity with the possibility of heavy rainfall

IMD kept round the clock watch on the system development, its movements and issued colour coded severe weather warnings at District level for next 5 days to State Disaster Management Unit, MCGM Mumbai, other stake holders like Railways, Agriculture, general public and media; 4-5 days in advance. Konkan belt and adjoining ghat areas were issued highest warning of Red, 3 days in advance. Along with this, possibility of squally weather with strong winds and its gustiness along and off the coast was also indicated in the daily bulletins. IMD also Impact based forecast to State Govt. and disaster management authorities with probable impacts.

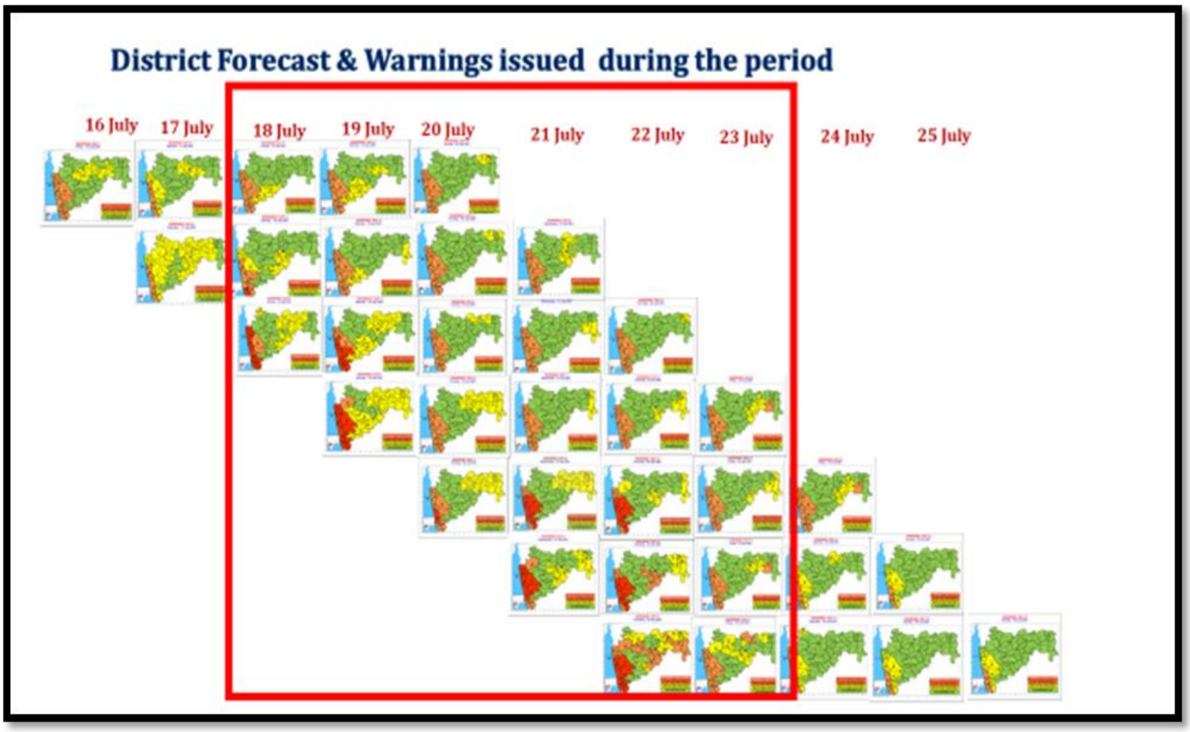
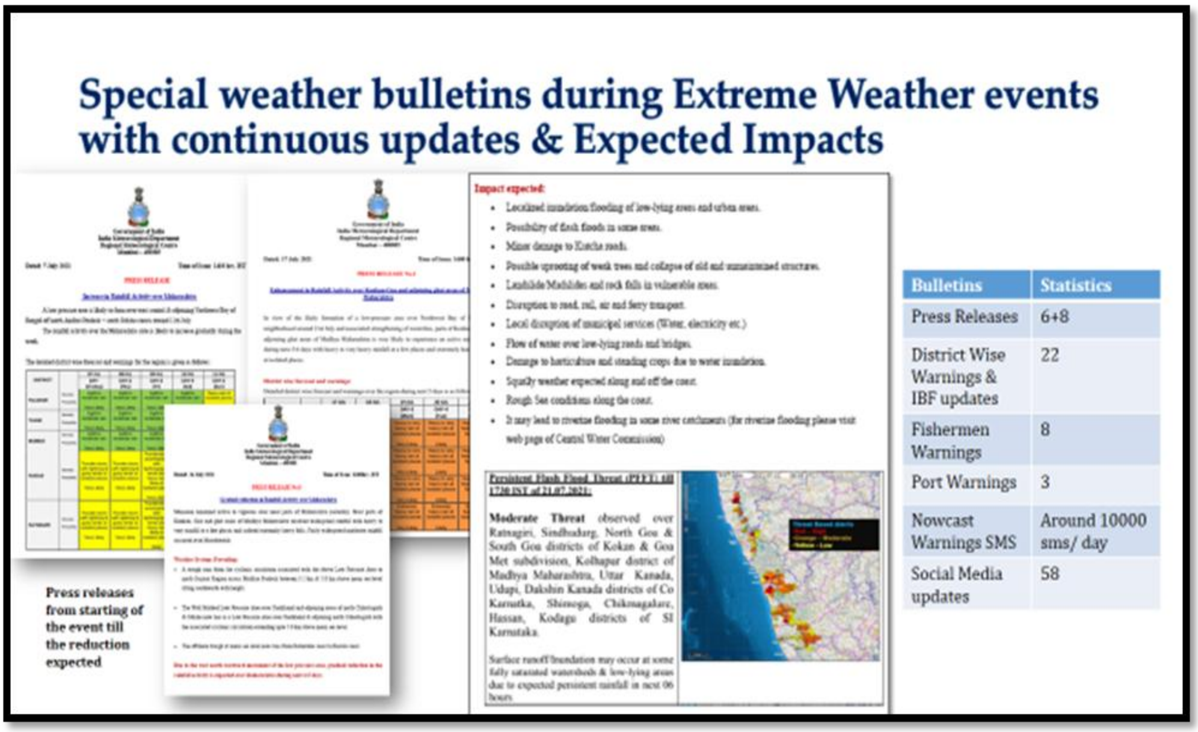


Fig (3.3.8): 5 day District wise rainfall and warning issued every day for the period 18-23July 2021

3.3.6 Dissemination of Warnings to different stake holders in the State:

The forecast and warnings were disseminated with extensive use of SMS broadcast, emails, over phones/faxes, websites and social media platforms like Twitter, Facebook etc so that warnings are received well in time for further planning by the Disaster Management Authorities and other agencies. Forecast and warnings are provided to public and various stake holders through print & electronic media. Personal interaction with stake holders and media were also made. **Daily Press releases** were also issued to the stake holders from 16th July 2021, regarding the expectation of severe weather over the region during 18-23rd July 2021.

IMD throughout kept round the clock watch on the system development, its movements issued colour code severe weather warnings; both for; state and district wise to public, disaster managers, and stake holders on real time. IMD also briefed the Cabinet, Govt of Maharashtra about the latest updates of situation and its further likely intensity on 18th July 2021, through a presentation at Mumbai. The rainfall event and its atmospherics features were continuously monitored round the clock by IMD with surface synoptic observatories, State Government Rain-guage network, Automated Weather Stations (AWS) network Satellite and DWR Mumbai and Goa products.



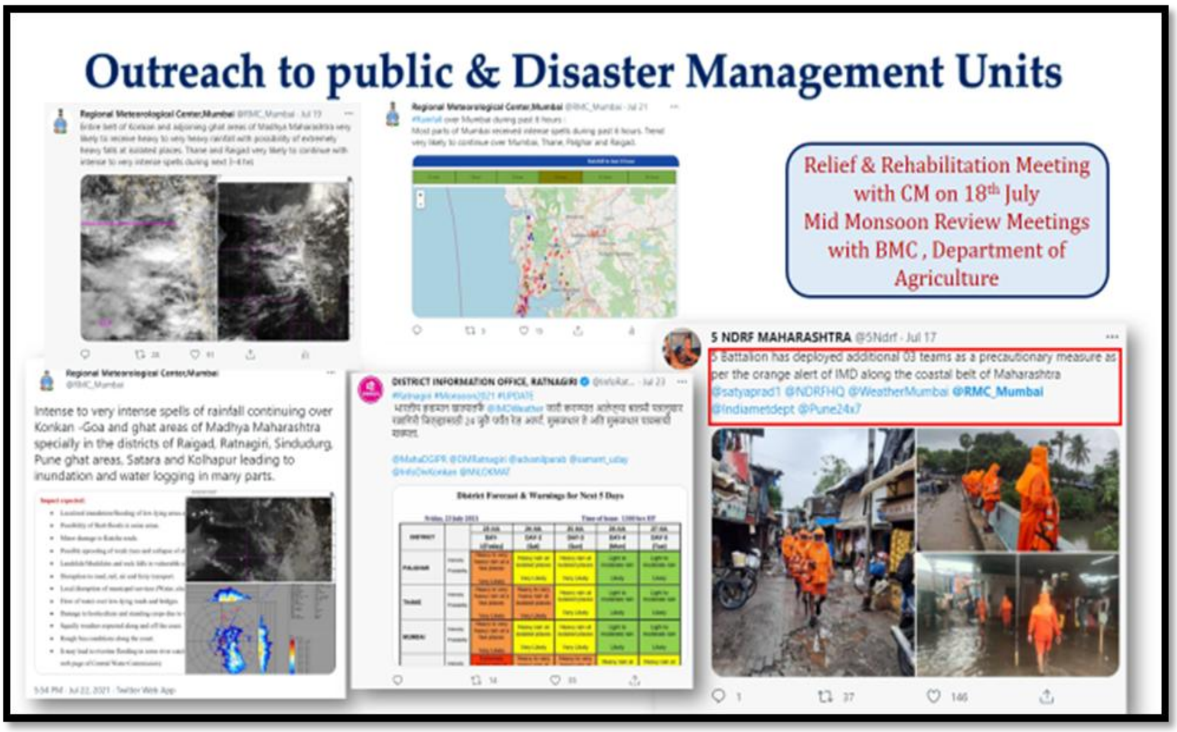


Fig (3.3.9): Special wather bulletins and continuous outreach to public provided during the period

3.3.7 Concluding Remarks :

Monsoon 2021 ended with a diverse monsoon activity over the Maharashtra. 2021 happened to be normal monsoon for Maharashtra with large number of high impact events. The extremely heavy rainfall of 18-24th July over Konkan and adjoining areas of Madhya Maharashtra leading flooding was under the combined influence of the westward movement of the low pressure area over North Bay of Bengal, presence of east west shear zone and off shore trough along west coast. The study highlights the role of typical monsoon synoptic systems in evoking heavy rainfall episodes over Maharashtra especially west coast.

RMC Mumbai effectively handled severe weather events over the region. Very good feedback was received from the user's side including general public, media and other stake holders for timely communication of severe weather warnings in advance. All the entire available observational network; surface, upper air, DWR and Satellite products weather charts, NWP guidance were fully utilised and there was no interruption in network during the period. The daily national VC guidance was also taken during the period. The district level warnings started well in advance and were put on the IMD Mumbai website and also the messages were sent to all concerned stake holders; Mumbai city disaster management unit MCGM, Disaster Management Unit, Govt of Maharashtra, Commissioner of Police, Railways, Agriculture and Media. Press Releases were issued from indicating the possibility of high impact event over the region. Impact based bulletins were also issued as per SOP followed by regular rainfall updates with possible impacts, till the event was over.

SOUTH WEST MONSOON 2021 OVER GOA

Saurav Mishra, Rahul M

Goa is a small State, comprising only of two districts – North Goa and South Goa, which are divided into 11 Talukas, having a total area of 3702 Sq Km. Goa is situated along Konkan Coast of India and has a coast line of 131 km. It has a partly hilly terrain with the Western Ghats rising nearly 1200 meters. There are two main rivers, i.e. Mondovi and Zuari. Goa receives most of its rainfall during Southwest Monsoon from June to September with an average of 2975.6 mm.

During 2021, though the Southwest monsoon set in over Kerala on 03rd June, 2021, 2 days after its normal date, it advanced over Goa on 05th June, i.e. 2 days before of its normal date of arrival over Goa**.** During the south west monsoon season, Goa state received 3157 mm rainfall against the long period average of 2976 mm (Fig.1) with percentage departure of actual rainfall from normal as 06% (Table 3.3.3 and Fig. 3.3.4), i.e. Goa state experienced rainfall for SW monsoon period in normal category. Monthly actual and normal rainfall is shown in (Fig.3.3.16) Rainfall departure for North Goa was 11% and South Goa was 02% (Fig.3.3.17)

Month wise rainfall distribution for Goa State

Month	Actual Rainfall (in mm)	Normal Rainfall (in mm)	Departure (%)
June	952	899	06%
July	1282	1069	20%
August	365	702	- 48%
September	558	306	82%
Season as a whole	3157	2976	06%

Table.3.3.2. Month wise rainfall distribution for Goa State during monsoon 2021

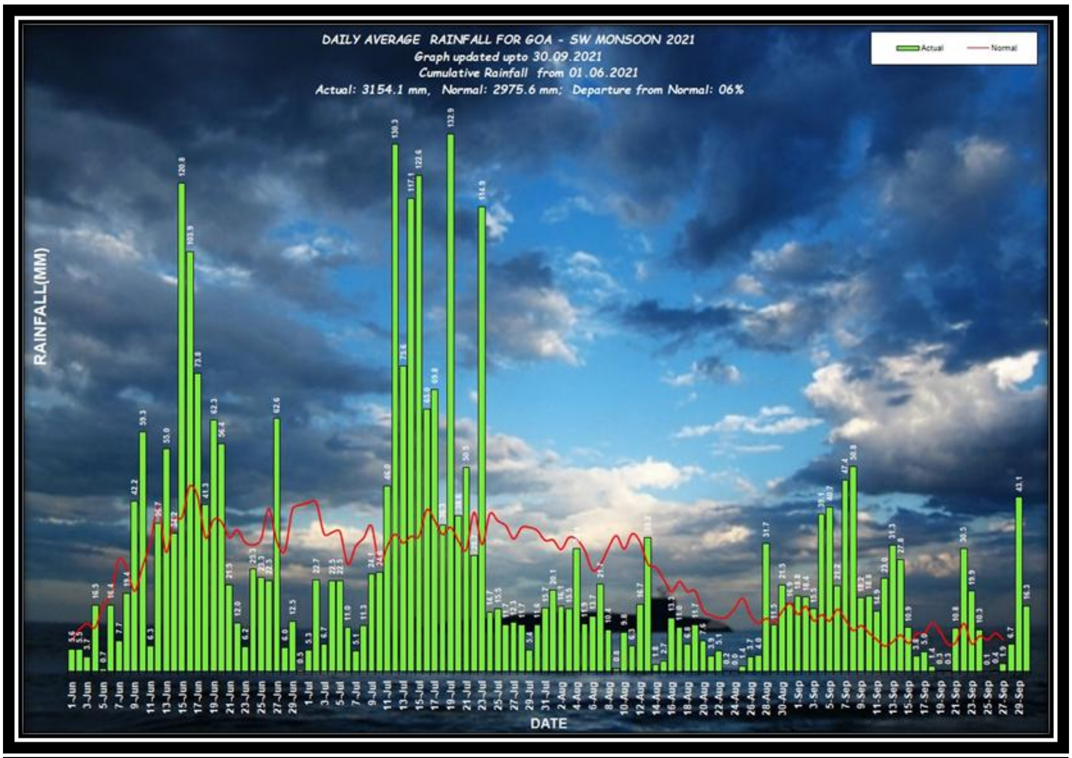


Fig.3.3.10. Daily average rainfall for south-west monsoon-2021

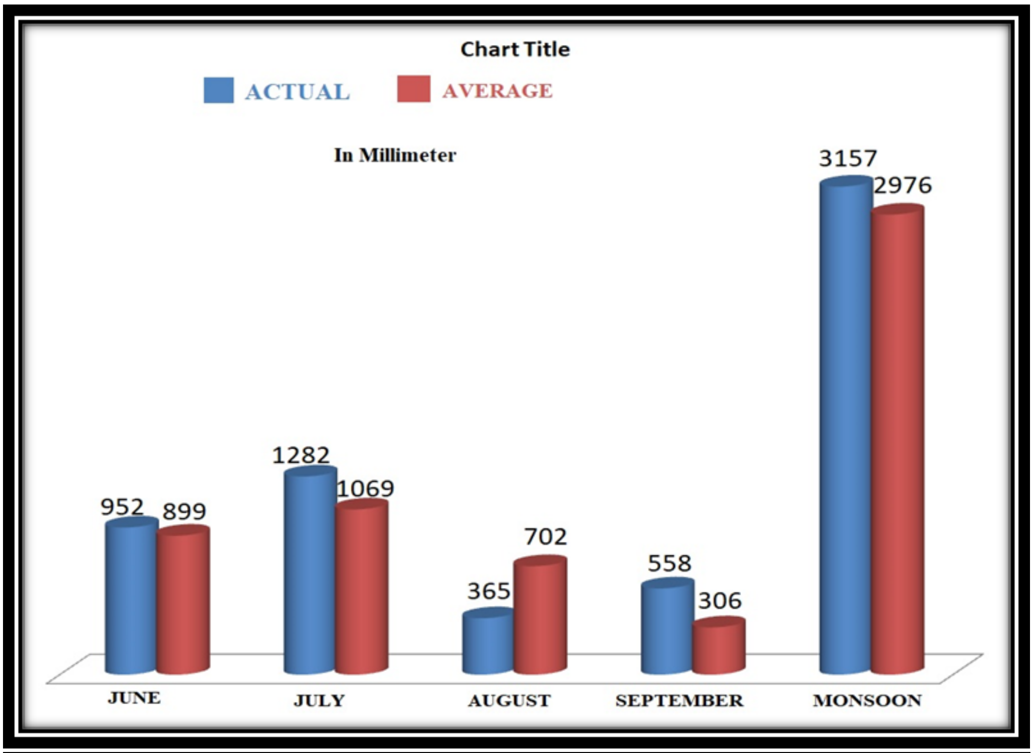


Fig.3.3.11 Month wise and seasonal actual and normal rainfall (in mm) for monsoon-2021.

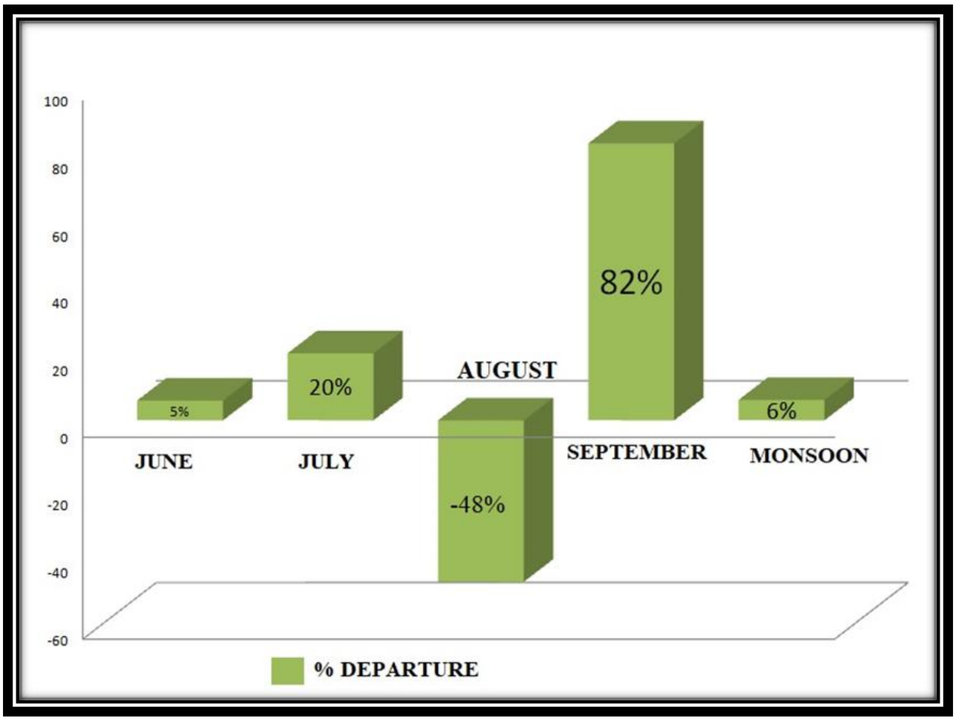


Fig. 3.3.12 Month wise and seasonal departure in rainfall (in mm) for Monsoon-2021.

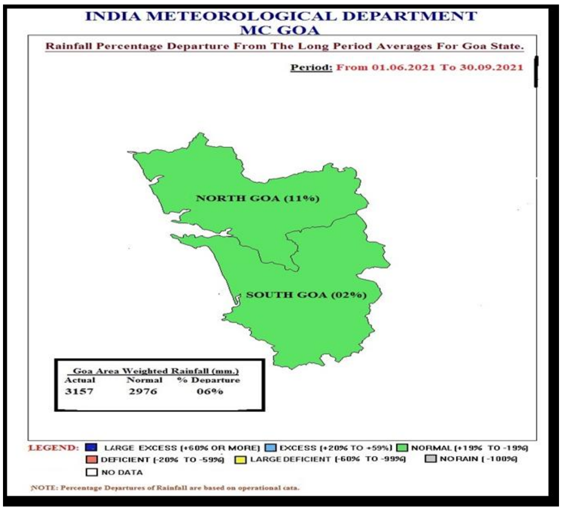


Fig. 3.3.13 District wise seasonal rainfall map (SW Monsoon 2021)

3.3.8 Heavy Rainfall spell over Goa during 11-24th July 2021:

Active Monsoon conditions prevailed over Goa state on 12, 13, 14, 15, 16, 17, 19, 21 & 23 July. The heavy rainfall spell over Goa from 11-24th July was under the combined influence of the westward movement of the low pressure area over North Bay of Bengal, presence of east west shear zone and off shore trough along west coast.

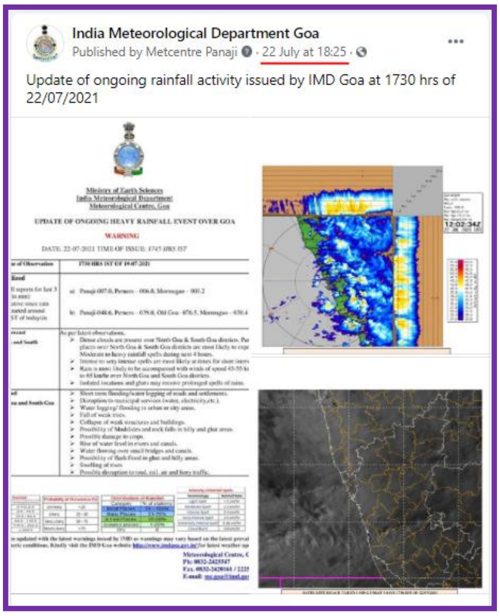
Heavy rainfall reported for 13 days, among this *extremely heavy rainfall* was realized at isolated places on 23rd July (Volpoi – 30 cm & Sanquelim – 21 cm). *Very heavy* rainfall was realized at *most places* on 19th July, at *many places* on 12th & 14th July, at *a few* places on 15th July & at *isolated* places on 23rd July. On 23rd July, eastern talukas of Goa such as Sattari, Dharbandora and Bicholim experienced flood-like situation which was termed as worst flood in 60 years. Even though only one casualty was reported, about 500 houses were damaged and hundreds of people had to be evacuated to shelters. State received 1281.9 mm of rain against the long period average value of 1068.9 mm. For the month of July, the rainfall distribution over Goa was in normal range of its long period average (20%)

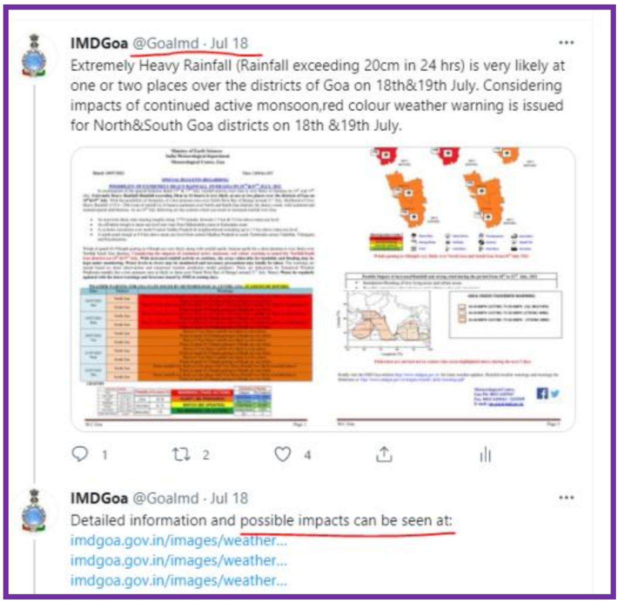
Period	Cumulative rainfall	Departure from Normal	Number of Extremely Heavy rainfall events
11th July to 24th July	1039.3 mm	**115%**	Valpoi(29cm)& Sanguem (21cm) reported on 23rd July
22nd July to 24th July	158.3 mm	**44%**	Valpoi(29cm)& Sanguem (21cm) reported on 23rd July

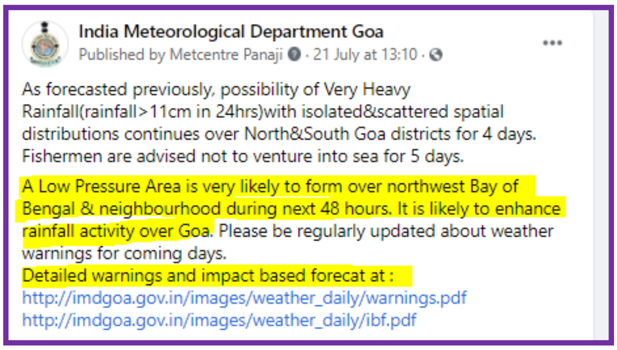
Meteorological Centre Goa, successfully implemented the impact based heavy rainfall forecast during monsoon 2021. Impact based forecasts were issued 48 days in advance, 24 hours in advance, and regular updates of 6 hourly interval or based on the severity of the system on the day of heavy rainfall. Accounts of social media platforms, whatsapp, conventional modes such as email, SMS, website etc. were used for dissemination of information.

Period	Based on impact, Red colour weather warnings were issued on
11th July to 24th July	18th July 19th July 22nd July 23rd July

Number of press releases where impacts for the state was mentioned	Number of Daily Impact based forecasts for Panaji and 2 districts of Goa	Number of 6 hourly impact based forecasts based on radar & satellite observations
7	15	14







3.3.9 Forecasted and realized impacts during July 11th to July 23rd 2021:

- Water logging/flooding of roads and low lying areas
- Fall of weak trees
- Collapsing of weak structures and buildings
- Localized disruption to municipal services (water, electricity, etc.)
- Short term inundation/ flooding in urban or city areas.
- Traffic congestions on main roads
- Possible disruption to road, rail, air and ferry transport
- Extensive Damage to Crops like, Paddy, Banana, Vegetables etc
- Mudslides and landslides in localized and vulnerable areas
- Rise of water levels in rivers and canals
- Water flowing over small bridges and culverts
- Possibility of Some communities / islands temporarily cut off /not accessible

MONSOON INTRA SEASONAL RAINFALL OSCILLATION OVER GUJARAT STATE 2021

Manorama Mohanty, F Vigin Lal

Indian summer monsoon which exhibits a wide spectrum of variability on Diurnal, Daily, Seasonal, Inter annual and Decadal time scales over different region/state of the country. Gujarat state is located in the extreme western part of India with Thar Desert in the north-east, Rann of Kutch in the west and the mighty Arabian Sea which envelops the state towards the south and south-west. The bulk of the rainfall activity over this region occurs during the months of July and August under the influence of synoptic scale systems. However during monsoon 2021, major rainfall activity occurred during June and September due to the typical synoptic situations. A study has been taken to analyse the intra seasonal variability of monsoon rainfall and associated characteristics for Indian Summer Monsoon 2021 over Gujarat state for Month of September has been carried out. Also occurrences of heavy rainfall to extremely heavy rainfall due to various synoptic systems formed over land and oceans has been analysed.

Gujarat state has two meteorological subdivisions Gujarat region and Saurashtra-Kutch. During monsoon season 2021, the subdivision Gujarat Region received normal rainfall of about 80cm (-12% departure), subdivision Saurashtra-Kutch received excess rainfall of about 62 cm (24% departure) and Gujarat state as a whole received normal rainfall of about 70 cm rainfall (2% departure). Though Gujarat state received normal rainfall during monsoon 2021 but there is large variation in monthly rainfall over the state. The state received 88 percent rainfall during June (-12 % departures), 60 percent during July (-40% departure), 30 percent during August (-70% departure) and 368 percent during September (268 % departures). From the weekly rainfall district rainfall data analysis it can be seen that over Saurashtra and Kutch region major spell of rain was during month of September (Fig: 3a, 3b).

Due to a few spells of rain during September 2021 the seasonal rainfall of the state became normal (Fig: 3a). This study has been carried out to analyse the variation of

intra seasonal rainfall and associated dynamical parameters for the month of September 2021. The time series of daily average rainfall over Gujarat state is shown in the Fig: 2. The data sets used for the study are u and v wind data from ERA5 reanalysis data set with 0.25*0.25 .deg horizontal resolution with vertical levels 1000 to 500 hpa standard levels for the month September 2021 with daily time steps (00UTC, 06UTC, 12UTC and 18UTC) and for area 68 .deg E to 72 .deg E and 20 .deg N to 24 .deg N; daily area averaged rainfall data from Rain gauges, AWS over Gujarat state for the period September 2021. In this study analysis is being done for the subdivision Saurashtra-Kutch during September 2021 as there was excess rainfall over the subdivision. During the first week of September the subdivision Saurashtra-Kutch received heavy to very Heavy rains (Fig 1a, 3b) with maximum rainfall of 17cm at Junagadh and Kutch districts as monsoon trough was running across Gujarat state.

Due to interaction of Low Pressure Area over southwest Madhya Pradesh & neighbourhood up to 7.6 km above mean sea level and the shear zone along Latitude 20°N between 3.1 km & 5.8 km above mean sea level, the state received heavy rain over Gujarat region and heavy to very heavy rain with isolated extremely heavy rain over Saurashtra-Kutch 2nd week of September (Fig 1a, 3b). The highest rainfall recorded on 9th September was 25 cm in Gir Somnath District. During 13th to 15th September 2021(Fig 1a, 3b) Gujarat state received an active wet spell due to the oscillation of monsoon trough up to Saurashtra coast and interaction with cyclonic circulation over Gujarat region. During the period heavy to very heavy rainfall with extremely heavy rainfall occurred over the state with highest rainfall recoded 52 cm recorded at Rajkot, 47 cm at Junagadh and 41 cm at Jamnagar on 14th September 2021. On 24th September Gujarat state received a good spell of monsoon rainfall (Fig 3.3.17a, 3.3.17b) with highest daily rainfall of 19 cm in Jamnagar district due to the cyclonic circulation over West Rajasthan. Last rainfall spell for the month was from 28th to 30th September 2021 (Fig 3.3.17a, 3.3.17b) due to intensification of Well-Marked Low Pressure Area into a Depression over northeast Arabian Sea & adjoining Kutch due to which highest rainfall recorded was 29 cm in Junagadh district on 30th September 2021.

The ERA5 data is used to compute relative vorticity and hovumuller plot is prepared for lower level(1000-850mb) and higher level (700-500) vorticity for the month September 2021 are shown in the Fig 3.3.17b. During the extremely heavy rainfall events, positive vorticity advection is observed at higher level also. Thus vertical advection of positive vorticity up to higher level can be considered as an indicator for extremely heavy rainfall forecast.

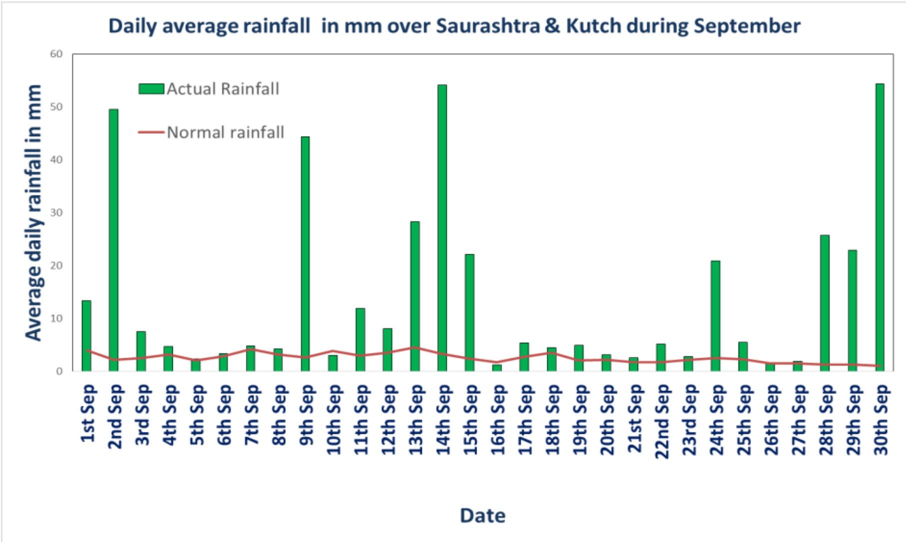


Fig3.3.14a : Daily average rainfall in mm over Saurashtra & Kutch during September

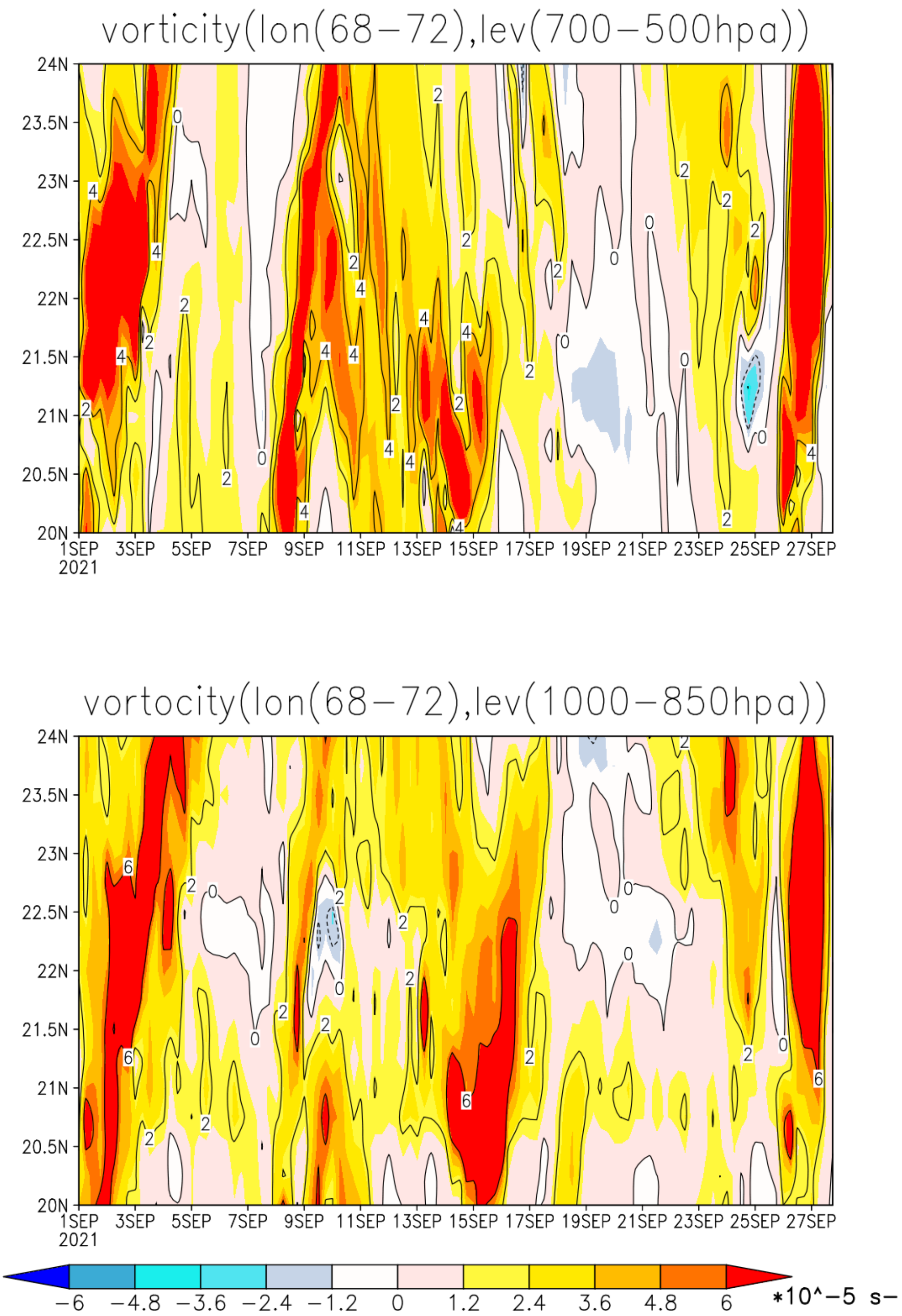


Fig 3.3.15b : Relative Vorticity Hovumuller plot September 2021

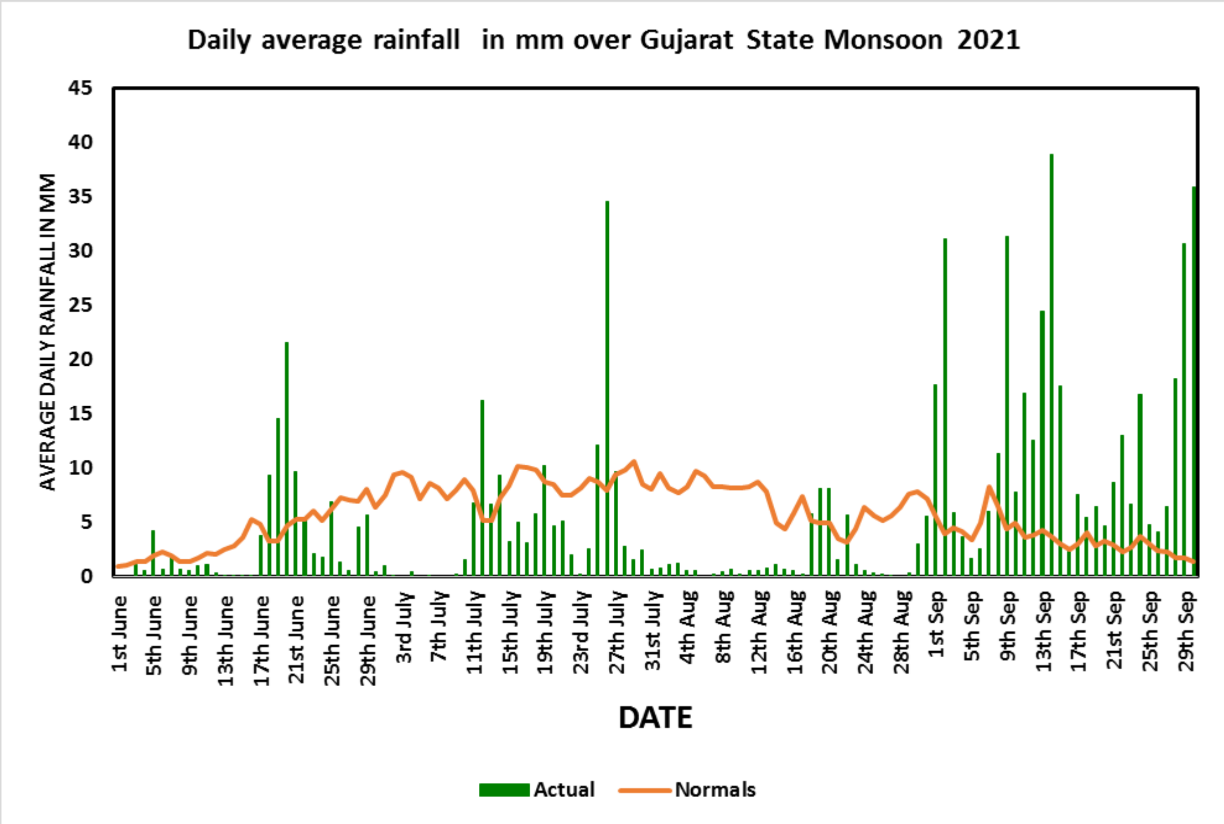


Fig3.3.16 : Daily average rainfall in mm over Gujarat State

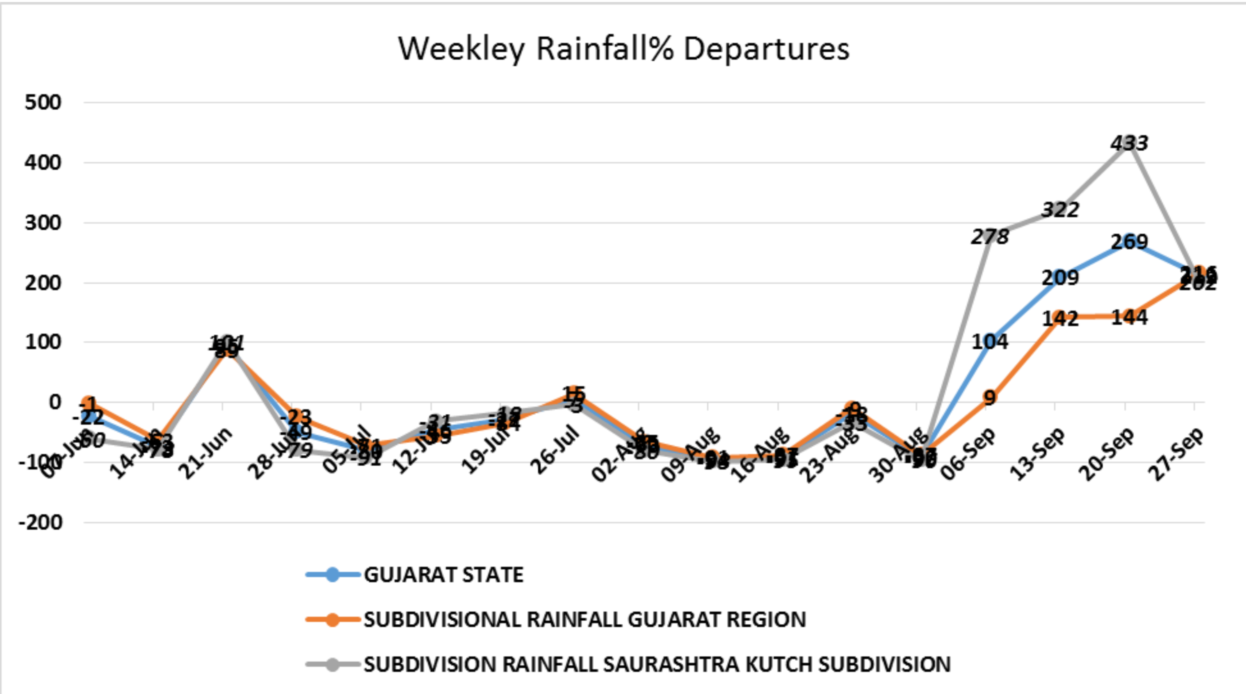


Fig 3.3.17a : Weekly percentage departures of rainfall from long period average

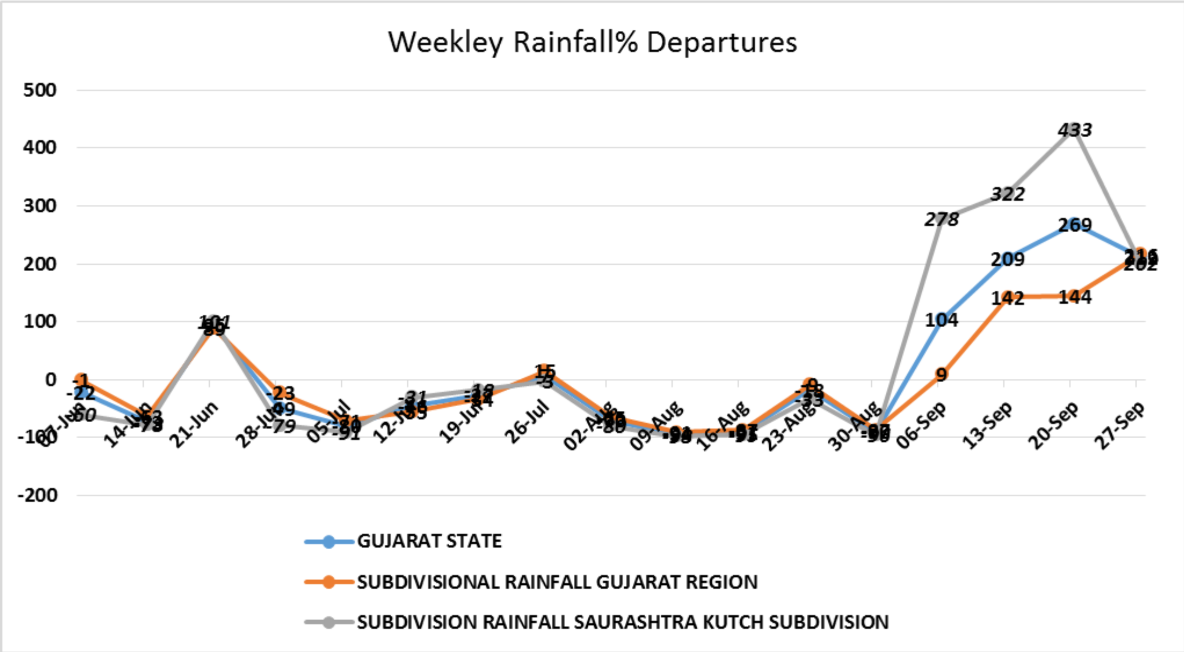


Fig 3.3.18a: Weekly percentage departures of rainfall from long period average

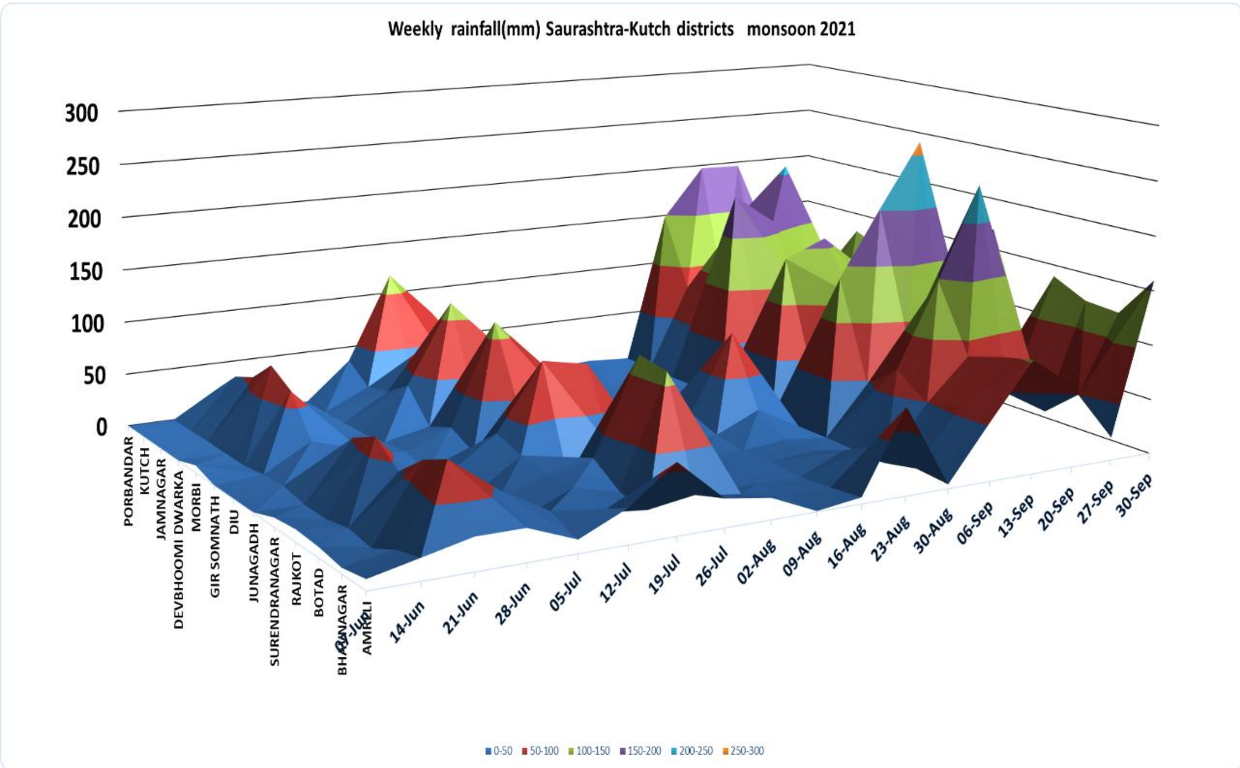


Fig 3.3.18b : Weekly rainfall (mm) over districts of Saurashtra-Kutch

3.4

Meteorological features associated with flood over Eastern India during southwest monsoon 2021

Sanjib Bandyopadhyay, H R Biswas, Umashankar Das, Vivek Sinha, Ashish Kumar, Anand Shankar,Sourish Bondyopadhyay, G K Das

In this chapter we have briefed about the meteorological analysis of three cases of flood situation – one over Gangetic West Bengal during 29th September to 1st October, 2021, another over Odisha during 12-15th September, 2021, and another over Bihar during 9-17th August, 2021.

3.4.1. Introduction

Water logging and floods are common misery in eastern Indian during the southwest monsoon season. Since, the region is close to the Bay of Bengal moisture is abundant in this region. Due to the position of monsoon trough, formation of a number monsoon low pressure area or depression and strong moisture incursion, lot of rainfall activity occur over the region. Many times the river basins and the soil remains near saturation which worsen the flood situation with intense or prolonged rainfall episodes.

During the period during 29th September to 1st October, 2021, intense rainfall episode took place over the Districts of Gangetic West Bengal. About 22 lakh people were affected in the districts of Paschim Medinipur, Paschim Bardhaman, Bankura, Birbhum, Howrah and Hooghly. Though the major rainfall occurred during 29th September to 1st October, 2021 the water logging lasted for several days even after rainfall reduced significantly or almost stopped. Flood conditions observed over some river in Odisha due to impact of rain-storms associated deep depression during 12th to 15th September 2021. In the state of Bihar, flood situation occurred during 9th to 17th August, 2021.

3.4.2. Physiography of EasternIndia

Eastern India consists of the six meteorological subdivisions, comprising of five states of eastern India namely West Bengal, Sikkim, Bihar, Jharkhand and Odisha. Sub Himalayan West Bengal (SHWB) and Sikkim form a single subdivision. West Bengal state consists of SHWB and the meteorological subdivision, Gangetic West Bengal (GWB). SHWB & Sikkim is dominated by orography mainly associated with Eastern Himalayas. GWB and Odisha is mainly coastal subdivision near Bay of Bengal whereas Bihar and Jharkhand is landlocked state/subdivision (Fig.3.4.1). Major river basins in eastern India are Ganga river basin in Bihar and West Bengal area, Odisha has three river basins namely Mahanadi, Subarnarekha, Brahmani and Baitarani As majority of tributary rivers of Ganga passing through Bihar and West Bengal, these two states are more prone to massive flood during monsoon season.

Fig.3.4.1: Major River Basin of Eastern India

3.4.3 Synoptic Situation associated with flood in GWB during 29th September-1st October, 2021

On 28th September, a Low Pressure Area was formed over Northwest Bay of Bengal & adjoining coastal areas of West Bengal with associated cyclonic circulation extending upto mid-tropospheric levels and thereafter it intensified into a Well-Marked Low Pressure Area over the same region at evening. On 29th September It lay over central & adjoining western parts of Gangetic West Bengalat morning and western parts of Gangetic West Bengal & adjoining Jharkhand at evening with associated cyclonic circulation extending upto mid-tropospheric levels on 29th September. Again on 30th September, it lay over North Jharkhand & adjoining Bihar with associated cyclonic circulation extending upto 7.6 km above mean sea level passing through North-West Jharkhand & neighbourhood. At evening on the same day, it lay over South Bihar & adjoining Jharkhand. On 1st October, it weakened as Low Pressure Area and lay over South-West Bihar & neighbourhood with associated cyclonic circulation extending upto 7.6 km above mean sea level and lay over West Bihar & East Uttar Pradesh on 2nd October and then it gradually moved far away. On 29th September, an east-west trough ran from cyclonic circulation associated with the Well-Marked Low Pressure Area over south Gujarat region and adjoining Gulf of Khambhat to the cyclonic circulation associated with the other Well-Marked Low Pressure Area over western parts of Gangetic West Bengal and neighborhood across Madhya Pradesh, Chattisgarh and Jharkhand extending upto 5.8 km above mean sea level.

3.4.4 Rainfall over GWB associated withLPS

The rainfall associated with the low pressure system (LPS) is shown in Fig. 3.4.2 and heavy rainfall (64.5 mm or more) is shown in Table-3.4.1. Several places GWB received heavy to very heavy rainfall with extreme heavy rainfall in some places. Also, historical exceptional heavy rainfall was recorded in some places in western districts of GWB.

Due to physiographic location and orientation of river basins, most of the rainfall over Jharkhand is ultimately run off to GWB. As a result massive flood observed over districts of Paschim Medinipur, Paschim Bardhaman, Birbhum, Howrah and Hooghly. Water logging and prolonged flood situation persisted even after ceasing rainfall.

Table- 3.4.1: Realized heavy rainfall (7 cm or more) over GWB

Date	Stations with 24 hours accumulated rainfall ending at 08:30 hours IST (in cm)
29/09/21	PINGLA 28, DURGACHACK 22, MOHANPUR 19, SAGAR 18, KHARAGPUR 17, MIDNAPORE(CWC) 17, KALAIKUNDA 17, KHIRPAI 16, DIAMOND HARBOUR 15, MIDNAPORE 15, CONTAI(STATE) 11, NANDIGRAM 11, CONTAI 10, AMFU KAKDWIP 10, ULUBERIA AWS 9, ULUBERIA (STATE) 9, ALIPORE 9, MANMOTHNAGAR 8, JHARGRAM (STATE) 8, JOYPUR(STATE) 7, JHARGRAM (PTO) 7, AMTA-I 7.
30/09/21	ASANSOL 43, LUCHIPUR 41, BANKURA 35, ASANSOL(CWC) 35, BANKURA(CWC) 23, HATWARA 23, DURGAPUR 22, KHARIDWAR 22, TUSUMA 19, PURULIA 17, KASHIPUR 16,SIMULA 14, KANSABATI DAM 14, PHULBERIA 11, NANDIGRAM 10, PURIHANSA 9, RAJNAGAR 8, PANAGARH(IAF) 8, HETAMPUR 8, TANTLOI 8, BURNPUR 8, RANIBANDH 7, SURI (CWC) 7 ,LALGARH 7,JOYPUR(STATE) 7,KANKSA (DSF) 7.
01/10/21	PURULIA 17, BURNPUR 13, SIMULA 8.

3.4.5. Damage in GWB due to the Flood during 29th September to 1st October

As per media report damage and loss due to the flood situation is as follows-

a). Houses damaged : 20000
c). No ofpeopleaffected : 22 lakhs
d). Humandeathtoll : 11

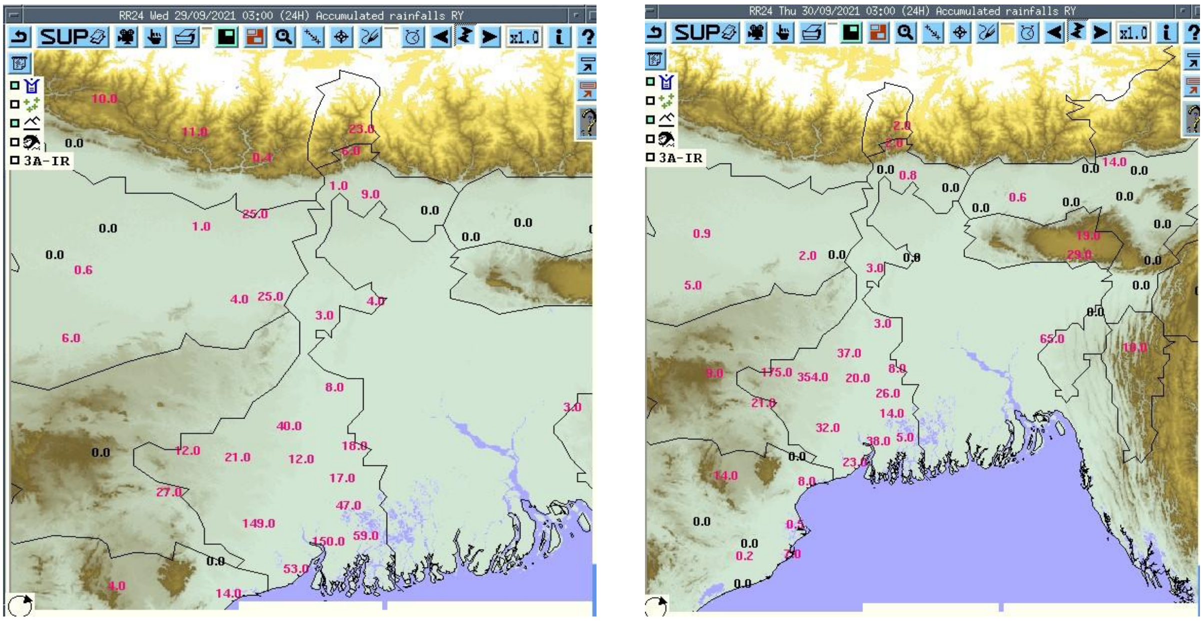


Fig.3.4.2: Realized rainfall distribution over GWB during 29-30th September, 2021.

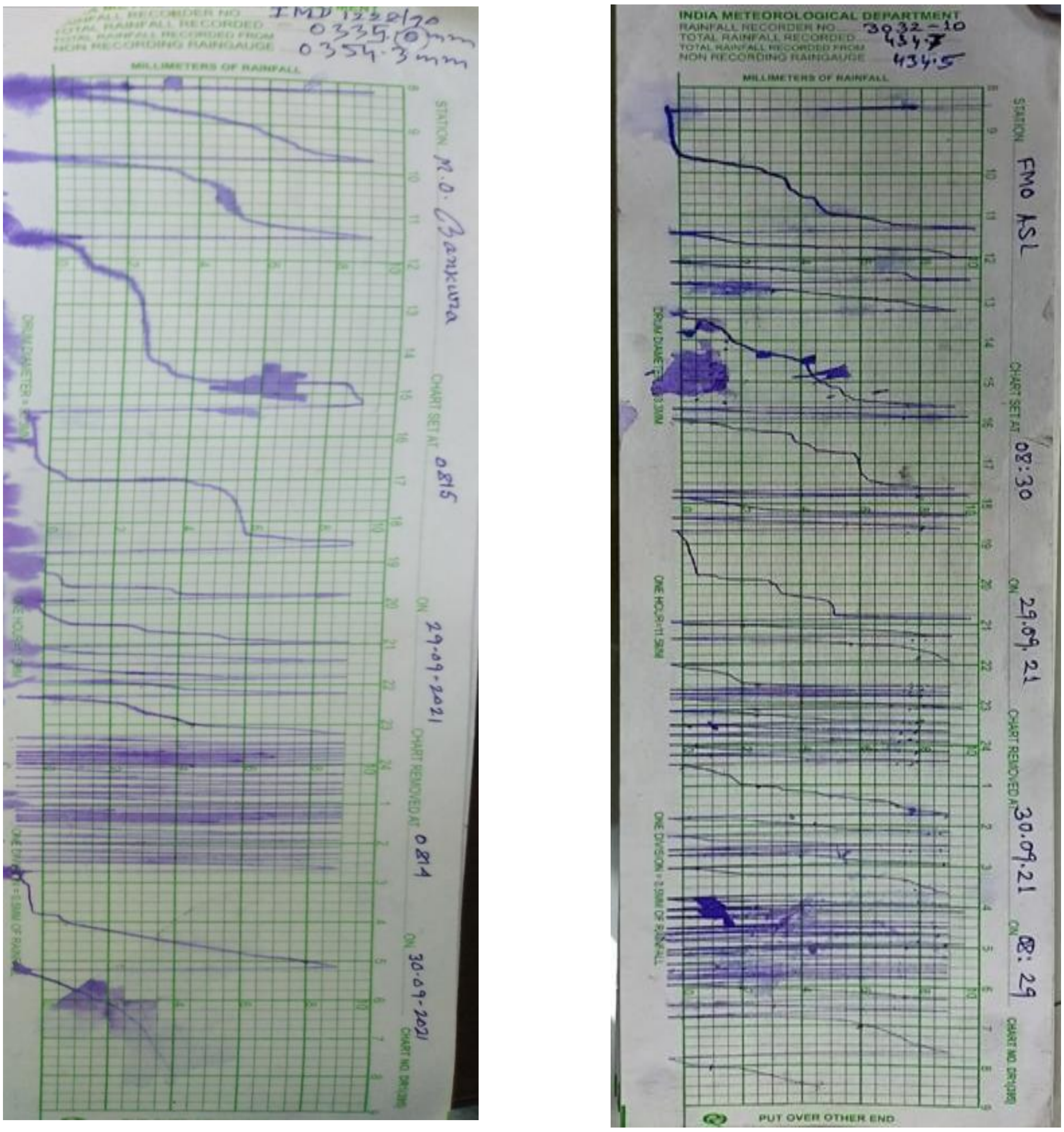


Fig.3.4.3: SRRG chart for Bankura and Asansol on 29th September, 2021.

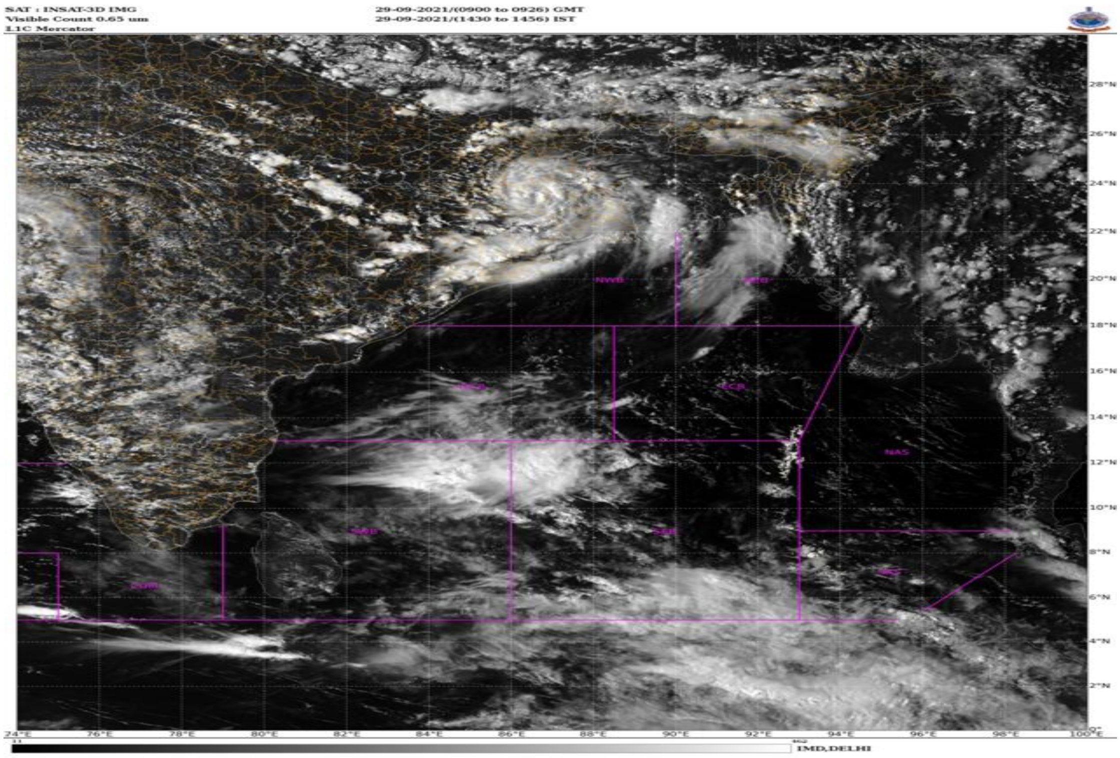


Fig.3.4.4: Satellite images of 29th September, 2021.

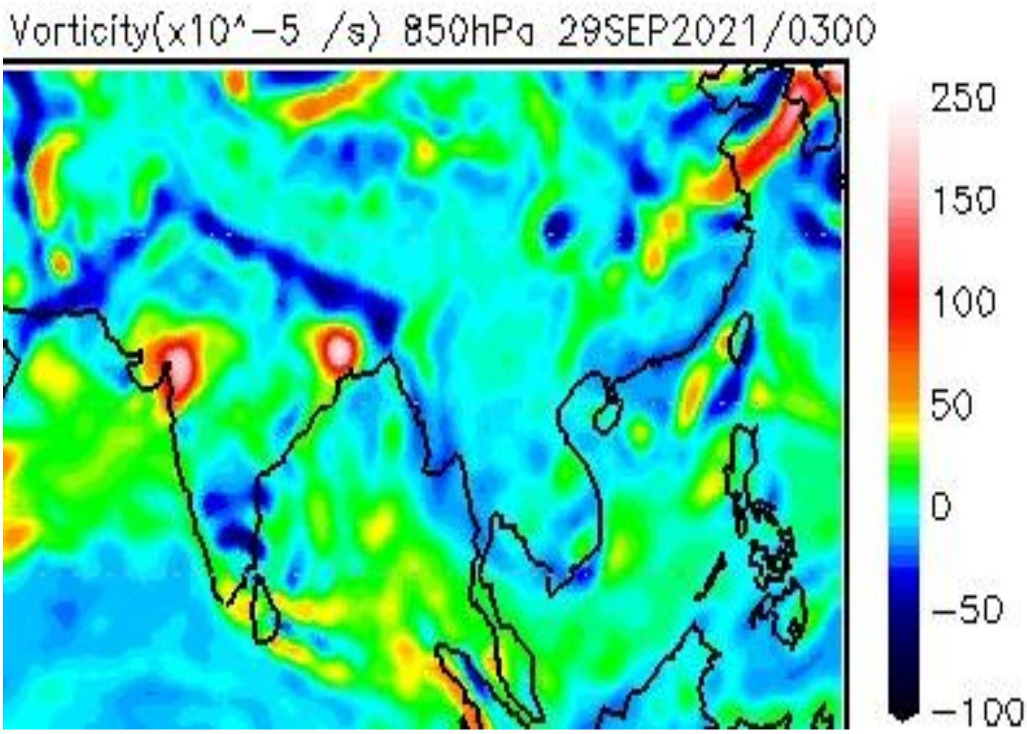
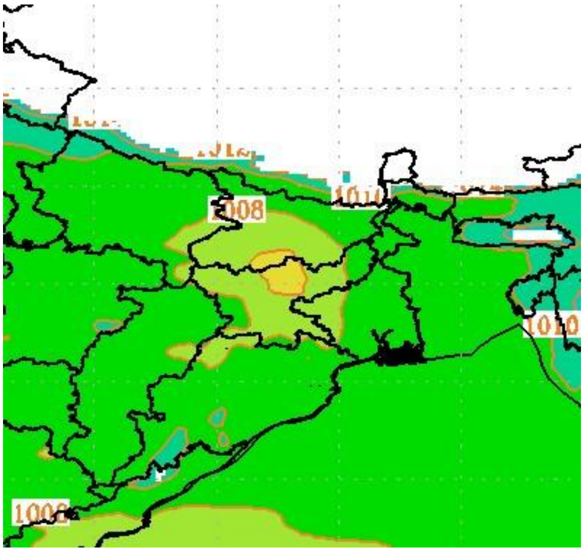


Fig.3.4.5: INSAT 3D Satellite derived vorticity of 29th September, 2021.



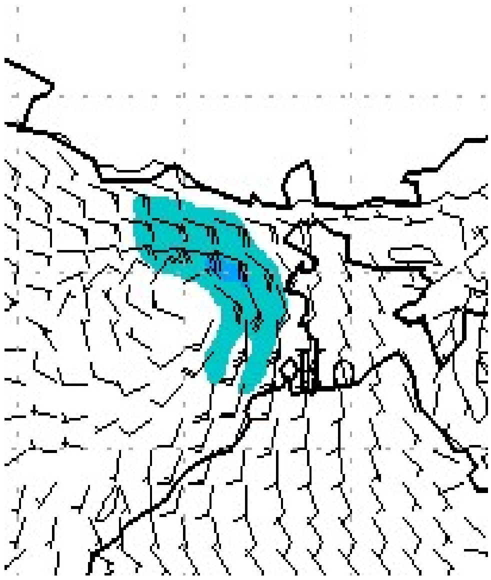


Fig.3.4.6: Left: IMD GFS model analysis for MSLP of 00 UTC of 30th September, 2021. Right: IMD GFS model analysis for 925 hPa wind of 00 UTC of 30th September, 2021.

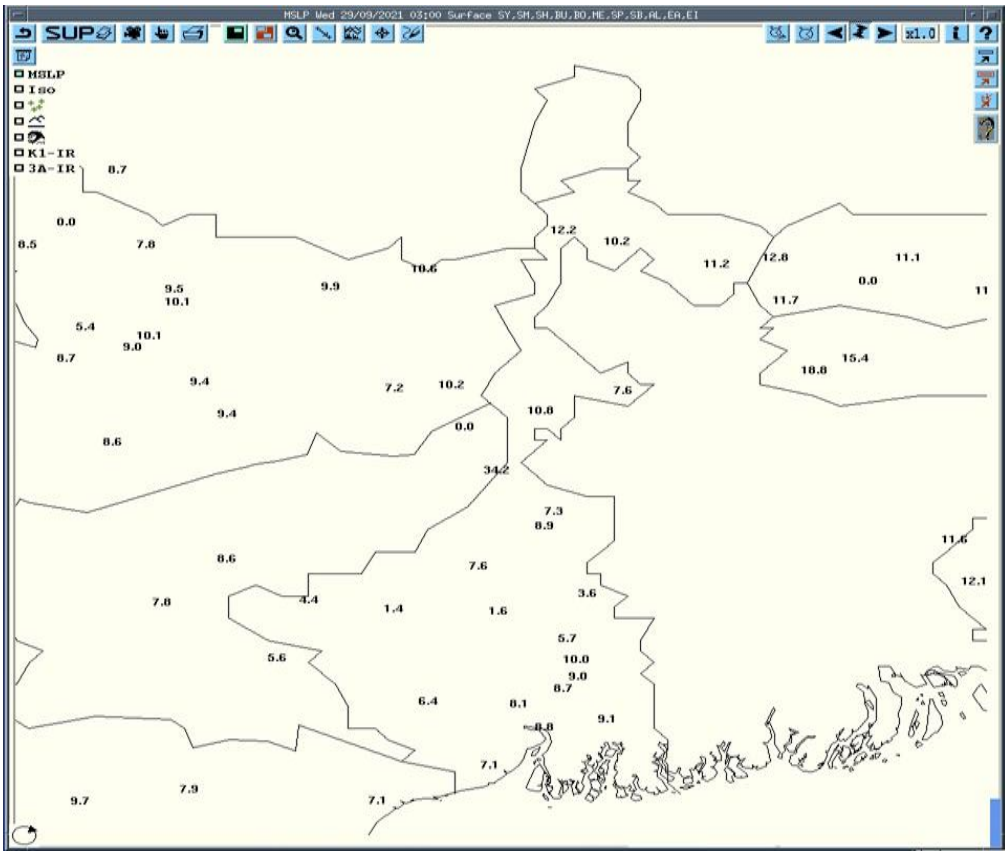


Fig.3.4.7: Realized distribution of mean sea level pressure on 29th September, 2021.

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Two dead, 22 lakh hit by floods in West Bengal

Shiv Sahay Singh

KOLKATA: OCTOBER 01, 2021 21:49 IST
UPDATED: OCTOBER 01, 2021 21:49 IST

SHARE ARTICLE PRINT A A A

Fig.3.4.8: Media report of a flooded area at Udaynarayanpur in Howrah district on October 1, 2021.

3.4.6. Synoptic Situation associated with massive flood in Odisha during 12th to 15th September 2021

Under the influence of a cyclonic circulation over Eastcentral Bay of Bengal (BoB) & neighbourhood, a low pressure area formed over Eastcentral & adjoining northeast BoB at 0000 UTC of 11th September and became more marked and lay as a well-marked low pressure (WML) area over northwest and adjoining westcentral BoB at 0000 UTC of 12th September, which further intensified into a depression over northwest BoB and adjoining Odisha coast at 1200 UTC of same day. At 0000 UTC of 13th September, the depression over northwest BoB & adjoining Odisha coast moved west-northwestwards, intensified into a deep depression and lay centered over the northwest BoB, very close to north Odisha coast, near latitude 20.5°N and longitude 86.9°E, close to the southeast of Chandbali, the system further moved west-northwestwards and crossed the north Odisha coast, close to the south of Chandbali between 0530 & 0630 hrs IST (0000 – 0100 UTC) of 14th September as a deep depression with maximum sustained wind speed of 30 knots, the deep depression over north interior Odisha continue to move in west-northwestward direction and weakened into a depression and at 0300 UTC of 14th September, over north Chhattisgarh & adjoining north interior Odisha, about 80 km west-northwest of Jharsuguda (Odisha) and about 120 km south-southeast of Ambikapur (Chhattisgarh). Track of the system is shown in Fig.3.4.9.

Under the influence of deep depression Odisha received widespread light to moderate rainfall activity with scattered heavy to very heavy rainfall activity with isolated extremely heavy rainfall activity from 11th to 15th. Southwest monsoon was active on 11th, 12th, 15th and vigorous on 13th& 14th of September 2021 over the State.

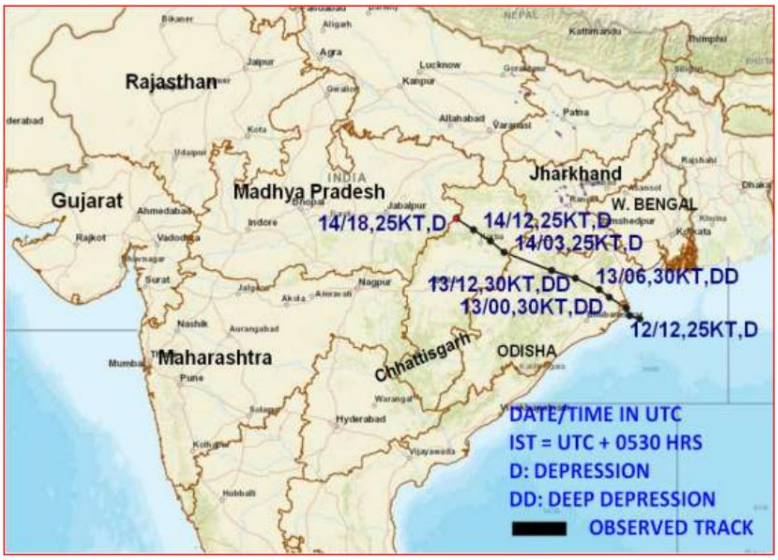


Fig.3.4.9: Observed track of deep depression over northwest BoB during 12th-15th Sep, 2021

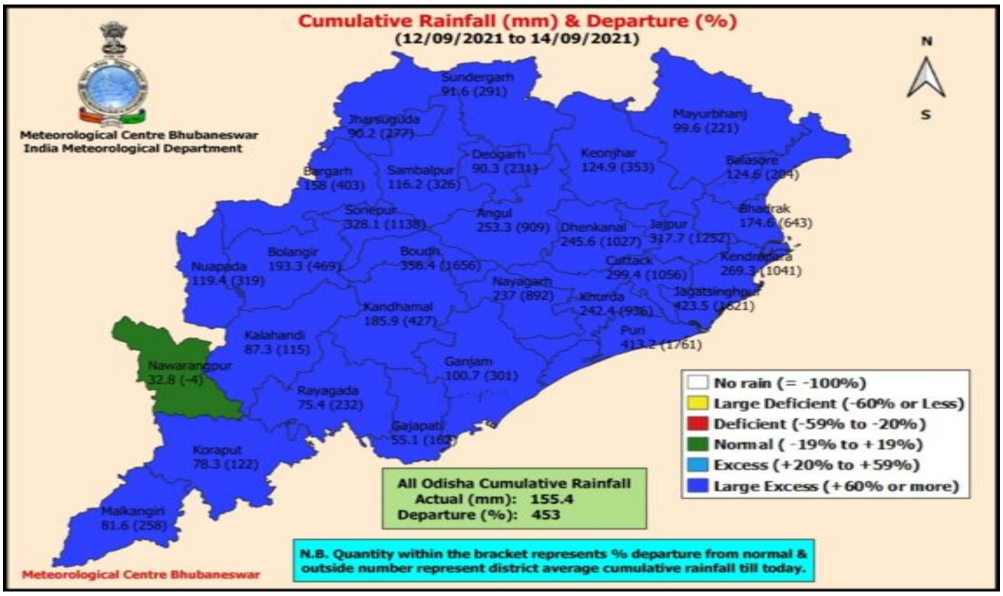
3.4.7. Rainfall over Odisha associated with Depression

Under the influence of deep depression Odisha received widespread light to moderate rainfall activity with scattered heavy to very heavy rainfall activity with isolated extremely heavy rainfall activity from 11th to 15th. Southwest monsoon was active on 11th, 12th, 15th and vigorous on 13th& 14th of September 2021 over the State. In the month of September Maximum amount of rainfall received in three days between 0830 hrs IST of 11th to 0830 hrs IST of 14th September in association with deep depression of amount 155.4 mm which is about 69% of September normal rainfall. Cumulative rainfall distribution with departure from normal during 12th to 14th September, 2021 is depicted in Figure.10. Station wise very heavy rainfall is shown in Table.2. Also distribution of heavy/very heavy/extremely heavy rainfall during 12th to 15th September 2021 is depicted in Figure.3.4.11.

Table-3.4.2: Realized chief amount of rainfall (12 cm or more) over Odisha

Very heavy rainfall (12cm or more) reported during 13 -15 sep 2021									
13th Sept2021				14th Sept2021				15th Sept2021	
District	Stations	District	Stations	District	Stations	District	Stations	District	Stations
BOUDHGARH	BOUDHGARH 18	KHURDA	TANGI 20	ANGUL	TALCHER 39	CUTTACK	MAHANGA 21	MAYURBHANJ	CHANDANPUR 15
	HARABHANGA 15		BHUBANESWAR 20		TIKARPARA 35		BANKI 19	KEONJHAR	GHATGAON 12
	KHAIRAMAL 14		BALIPATNA 18		BANARPAL 25		NARSINGHPUR 19	BALASORE	BHOGORAI 12
CUTTACK	KANTAPADA 38		BOLAGARH 15		ANGUL 20		ATHGARH 16	SUNDERGARH	SUNDERGARH 12
	NIALI 37		BANPUR 14		ATHMALIK 20		TIGIRIA 13		
	NARAJ 15	NAYAGARH	NAYAGARH 15		RAJKISHORENAGAR 18		SALEPUR 13		
	MAHANGA 15		KHANDAPARA 15	BALASORE	RAJGHAT 16		NARAJ 13		
	SALEPUR 14		ODAGAON 13		BALASORE 14		CUTTACK 12		
	MUNDALI 13		RANPUR 13	BARGARH	PAIKMAL 24	JAJPUR	BARI 21		
	BANKI 12	PURI	ASTARANGA 53		GAISILET 21		JENAPUR 21		
	CUTTACK 12		KAKATPUR 53		JHARBANDH 18		BINJHARPUR 17		
JAGATSINGHPUR	BALIKUDA 44		PURI 34		PADAMPUR 16		CHANDIKHOL 16		
	ALIPINGAL 36		GOP 33	BOLANGIR	PATNAGARH 25		SUKINDA 14		
	RAGHUNATHPUR 32		SATYABADI 33		BOLANGIR 24		DANAGADI 14		
	KUJANGA 27		NIMPARA 30		BELPADA 22	KANDHAMAL	PHIRINGIA 21		
	JAGATSINGHPUR 26		PIPILI 26		AGALPUR 18		PHULBANI 18		
	TIRTOL 25		BRAHMAGIRI 24		KHAPRAKHOL 16		TIKABALI 14		
	PARADEEP CWR 22		KRISHNAPRASAD 18		SALEBHATTA 15	KEONJHARGARH	DAITARI 16		
JAJPUR	CHANDIKHOL 22	SONEPUR	BIRMAHARAJPUR 20	BOUDHGARH	BOUDHGARH 26		TELKOI 13		
	BINJHARPUR 15		ULLUNDA 15		KANTAMAL 23	NAWAPARA	NAWAPARA 20		
	BARI 13		SONEPUR 15		HARABHANGA 19		KOMNA 13		
	JAJPUR 12				KHAIRAMAL 16	NAYAGARH	BARMUL 22		
KANDHAMAL	PHULBANI 15			DHENKANAL	HINDOL 24		GANIA 19		
KENDRAPARA	KENDRAPARA 28				PARJANG 23		DASPALLA 12		
	MARSAGHAI 27				KAMAKHYANAGAR 20	SONEPUR	BIRMAHARAJPUR 37		
	DERABIS 21				ALTUMA 20		SONEPUR 28		
	GARADAPUR 17				KANKADAHAD 18		TARVA 20		
					BHUBAN 17		ULLUNDA 15		
					DHENKANAL 16		DUNGURIPALLI 12		

Fig.3.4.10: Cumulative rainfall distribution with departure from normal over Odisha during 12th to 14th September, 2021.



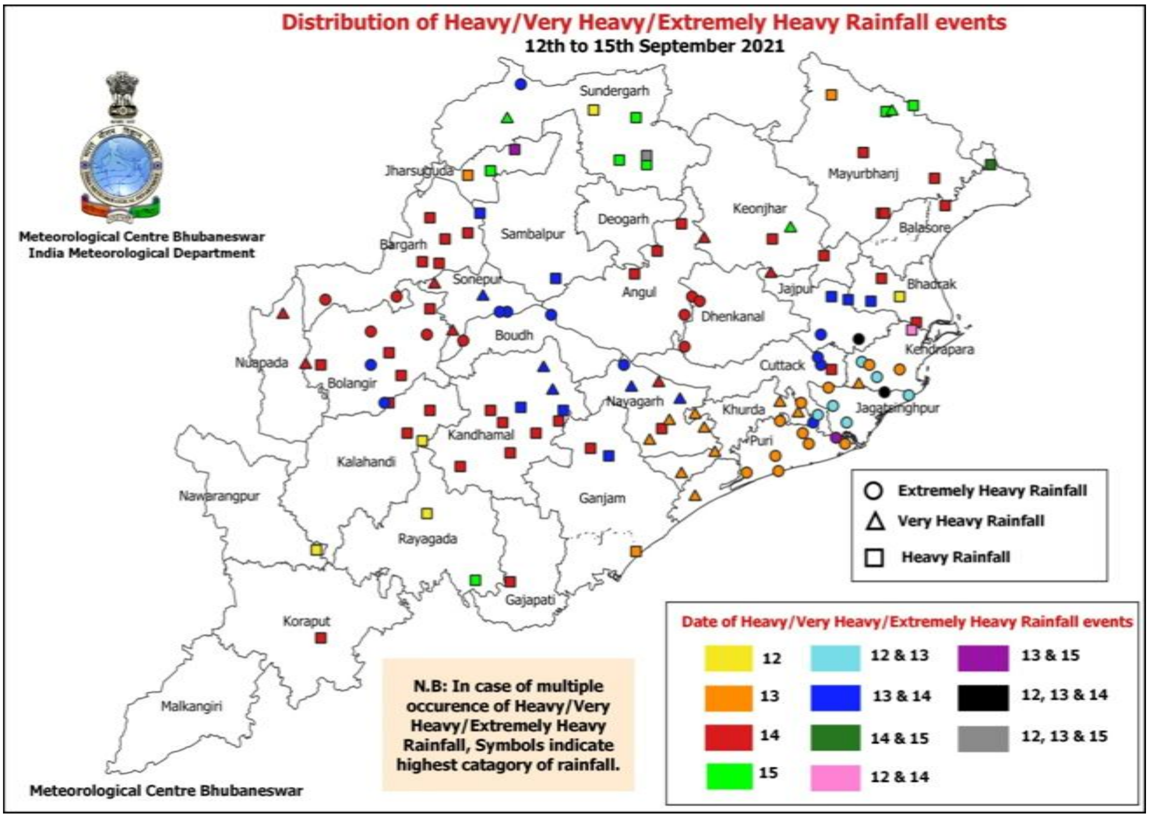


Fig.3.4.11: Distribution of heavy/very heavy/extremely heavy rainfall over Odisha during 12-15th September, 2021

3.4.8. Damage in Odisha due to the Flood during 12-15th September, 2021

As per preliminary report of State authority the following damages occurred over the state.

No. of Blocks Affected	139
Human Causality	6
Livestock affected	3043 (broiler 3000 and others 43)
Houses Damaged	7540
Roads cut off	286
Agriculture area Affected (hect)	127108

6 (Six) human causalities have been reported. (3 three) in Kendrapara district due to wall collapse, 1 (one) in Khurda district due to drowning, 1 (one) in Ganjam district due to wall collapse and 1 (one) in Sonepur district due to wall collapse). In addition to above some media report with photographs of damages is depicted in Figure 3.4.12 and 3.4.13.

Fig.3.4.12:

(a) Vehicles wade through a waterlogged road during rain in Puri, on September 12, 2021 (source: https://www.indiatoday.in/ dated 14/09/2021)

(b) Bhubaneswar railway station (source:https://www.downtoearth.org.in/ dated 13/09/2021)

(c) A tree uprooted on Nandankanan-KIIT Road in Bhubaneswar (source:https:// https://odishatv.in// dated 13/09/2021)

(d) Heavy rain in the wake of a deep depression in the Bay of Bengalis likely to have caused the accident on a bridge over river Nandira when the goods train was on its way from Firozpur to Khurda Road

(source: https://economictimes.indiatimes.com/ dated 14/09/2021)

Fig.3.4.13: Water logging and causality of 3 people in Puri district during 12 - 13th Sept,2021(Ref. Samaj local newspaper).

3.4.9. Synoptic Situation associated with massive flood in Bihar during 9 to 17th August, 2021

There was aWell-Marked Low Pressure Area over Northwest & adjoining West central Bay of Bengal with associated cyclonic circulation extending up to 7.6 km above mean sea level tilting southwards with height which become concentrate into a Depression over Northwest Bay of Bengal during this period.There was a trough at mean sea level from Jaisalmer, centre of Low Pressure Area over East Rajasthan to the centre of Low Pressure Area over east-central & adjoining north-east Bay of Bengal across Nowgong, Pendra Road, Sambalpur, Puri having extension upto 0.9 km amsl on 11th which shifted towards south merged with depression Deep Depression over north coastal Odisha on 14th August.

3.4.11 Intense Rainfall over Bihar

There were different diagnostic, prognostic and synoptic meteorological features which may be attributed as a plausible explanation of this intense prolonged rainfall epoch, which lasted for more than a week together during 09 – 17 August 2021. Synoptically, during this epoch most of the time the eastern branch of the seasonal trough/secondary trough was either at its normal position or moves towards south resulting into direct inflow of moisture laden winds in the lower levels of the region from Bay of Bengal and the presence of LOPAR with extended upper air cyclonic circulation up to mid-tropospheric levels over Bihar & neighborhood in association with a trough in mid-tropospheric westerlies. These large scale synoptic settings along with existing dynamical/thermo-dynamical atmospheric setup, large scale moisture inflow & convergence occurred over this region which caused widespread rainfall activity over this region resulting into floods.

During the first fortnight of august 2021, fairly wide spread to wide spread rainfall occurred over Bihar, isolated heavy accompanied with very heavy falls. The meteorological conditions responsible for such rainfall activity may primarily be attributed to the diurnal oscillation of the eastern end of Seasonal Trough. The simultaneous presence of these systems along with different atmospheric geophysical settings in concurrence with underlying complex physiographic conditions resulted into large scale moisture incursion& convergence due to strong South/Southwesterly winds in lower and mid tropospheric levels leading to a prolonged spell of heavy rainfall in river catchment of different Basin.

Table 3.4.3 : Realized Intense Rainfall Amounts (Intensity: 5 cm & above)

Date	***Station wise Rainfall amount (in cm)***
09-Aug-2021	Supaul(6.6), Triveniganj(5.4),Basua(5.4), Brahampur(6.8), Chewara(7.7),Gaya(5.7),Jamui(5.6),Sripalpur(7.8)
10-Aug-2021	Birpur(5.8),Dhengbridge(9.0), Belsand(5.2),Hayaghat(5.3), Mushahari(6.2), Tarari(8.8) Bounsi(5.6)
11-Aug-2021	Madhwapur(9.2),Galgalia(6.5), Hayaghat(7.6), Siswan(8.5)
12-Aug-2021	GALGALIA (6.2), THAKURGANJ (13.1), Taibpur(9.6), Siliguri(10.6), Baltara(8.8), Rosera(7.4), KESSARIAH(5.5), MUSHARI(9.0), MUZAFFARPUR(8.0), SAHEBGANJ(12.6),SARAIYA(7.5),PUSA(7.4), JALALPUR(6.2),MARHAURA(7.6),MARSRAKH(5.6),HUSSAINGANJ(5.9),MAHARAJGANJ(12.0),PACHRUKHI(7.1), SISWAN(7.7), VAISHALI(7.4),Dumariaghat(11.0) , RAFIGANJ(5.8), GOGRI(6.8), Khagaria(5.8)
13-Aug-2021	Jokihat(8.0), Salkhua(5.7), Sour Bazar(5.9), Triveniganj(7.8), Sonbarsha(17.0), BENIBAD(10.2), Dhengbridge(8.5), Bairgania(8.4), KAMTAUL(7.8), Belsand(6.6), Saulighat(5.6), Jainagar(5.1), Khadda(8.2) MANIHARI(6.3), Kahalgaon(6.1)
14-Aug-2021	Bahadurganj(10.1),Thakurganj(8.9),Taibpur(5.5),Dhengraghat(5.5),Siliguri(6.7), Bagha(7.6),Tribeni/Balmiki(6.0),Khada(8.7)
15-Aug-2021	Bhimnagar(6.2),Dumariaghat(9.5),Gaunaha(8.4),Mahua(8.0),Sahebganj(7.8),Mehsi(6.8),Lalbegiaghat(6.5),Barauli(5.6),Patahi(5.5),Minapur(5.3)
16-Aug-2021	Kadwa(6.5), BENIBAD(10.8), CHAKIA(5.3),MEHSHI(6.5), MUSHARI(11.1),MUZAFFARPUR(7.9),REWAGHAT(5.9),SAHEBGANJ(6.2),SISWAN(8.2),VAISHALI(9.5),Chatia(7.0),Lalganj(8.0)
17-Aug-2021	Birpur(15.6), Bhimnagar(11.0), Siliguri(7.7), Supaul (5.9), Dhengbridge(8.8),

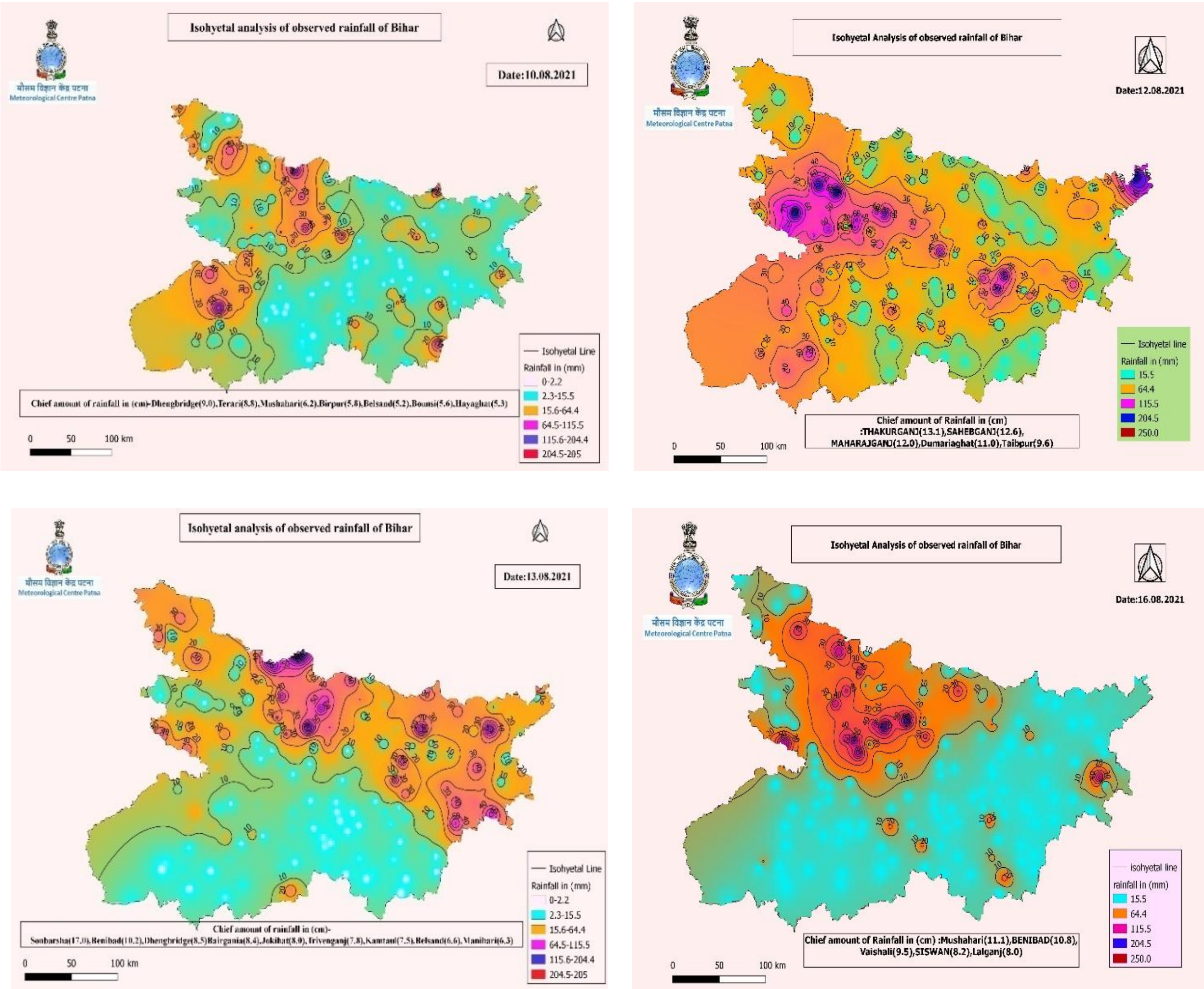


Fig. 3.4.14 : Isohyetal Analysis of observed rainfall of Bihar (0300 UTC) (a) 09th, (b) 11th (c) 13th & (d) 15thAug 2021.

3.4.12 Monitoring of Meteorological condition and issue of advisory/warnings by RMC Kolkata

The above described adverse meteorological phenomena was monitored by ACWC Kolkata round the clock during with the help of Satellite picture, conventional chart, DWR Kolkata, regional and national NWP model along with consultation/guidance of NWFC, NewDelhi.

Information on Synoptic Situation and heavy rainfall warning and advisories issued to Chief Secretary, Govt of WestBengal, Secretary, Disaster Management, Govt of WestBengal. Heavy rainfall warning was issued to Chief secretary, Secretary Disaster Management, Secretary Home Department, Gov. of West Bengal; DMs of all districts of West Bengal; Principal Chief Engineer (Bridge), Eastern & South Eastern Railway, Coal India Ltd., GM Eastern Coalfield Ltd. For West Bengal.

Fisherman Warning, Port Warning were issued to the concerned authority well in advanced and loss has been minimized.

DVC Authority has been provided catchment wise QPF forecast from DVC Unit during the period.

All the mode of communication like telephone, E-mail, Websites, Whatsapp has been used for dissemination of advisory and warning. Press release has been issued & Electronic and prints media has been briefed regularly. communications like telephone/fax, internet, website, e-mail, WhatsApp to the concerns State Government disaster Manager along with personal briefing to Senior Officer of Government and media by RMC Kolkata were very much effective for management of adverse disaster situation.

3.4.13 Monitoring of the system and weather Warnings by MC Bhubaneswar

The Depression was closely monitored by Meteorological Centre, Bhubaneswar under guidance of RMC Kolkata and NWFC, New Delhi. Information on Synoptic Situation and heavy rainfall warning and advisories, nowcast issued to various authorities of Govt. of Odisha, Principal Secretary, Revenue & Disaster Management, Principal Secretary, Dept. of Agriculture, Principal Secretary, Department of Water Resources, Special Relief Commissioner (SRC), M.D., OSDMA, Govt. of Odisha, RDC, Central Division/ Southern Division/ Northern Division, AIR Cuttack / Doordarshan , print and electronic media etc.

QPF and daily rainfall status was provided to Central Water Commission and water resource department, Govt. of Odisha regularly in time. All the mode of communication like telephone, E-mail, Websites, Whatsapp /SMS, regional and national electronic and print media has been used for dissemination of advisory and warning. The extent of damages due to such natural disaster event was mitigated with the advent of early warnings and active disaster response system of state disaster authority.

3.4.14 Monitoring of the system and weather Warnings by MC Patna

Behavior of this prolonged intense widespread to fairly widespread rainfall epoch over Bihar in the later phase of 1st fortnight of August during SW Monsoon-2021 has been carried out in terms of routine warning issued from MC, Patna. Based on the fundamental tools and valuable inputs from the conventional Synoptic Charts, Satellite pictures, various advanced Prognostic & Diagnostic Geophysical parameter, Radars, Global and Regional NWP model products heavy rainfall warning and advisories issued to various administrative authorities and end users of the state during the epoch of this weather event.

3.5

THE HEAVY RAINFALL EPISODE OVER ASSAM AND MEGHALAYA DURING 28-30 JUNE 2021

K. N. Mohan, S. Das, V. H. Arun. Kumar, H. Baisya andS.O. Shaw,

In this chapter,an analysis of the heavy rainfall episode during 28-30 June 2021 overAssam and Meghalaya has been discussed. During the period some of the stations in Khashi Hills district recorded more than 50 cm in 24 hours.

3.5.1 Introduction

Northeast region receives frequent heavy rainfall during the South-West Monsoon (SWM) season. The presence of the hills and their orientations and also the interaction of the monsoon current with the orography of the region is considered as one of main factors that cause heavy rainfall over the region.Also during the weak or break monsoon condition when the monsoon trough lies along the foot hills or passes through the northeast region (NER) causes heavy rainfall over the region.

TheSWM2021 advanced and covered the entire region on 8th June. It retreated from most parts of the region on 12th October and on 23th October it was withdrawn fron the entire NER.

During SWM 2021, Seasonal Rainfall was deficient over all the three meteorological subdivision of NER. Arunachal Pradesh received 1294.0 mm rainfall with departure: -25%, whereas Assam & Meghalaya and NMMT sub-divisions received 1385.80mm (Departure: -22%),and 964.0 mm (Departure: -32%) respectively.

Though the seasonal rainfall was deficit over the region, there were a few occasions when the region received heavy rainfall activity. The most prominent heavy rainfall episode was during 28-30 June 2021 when Meghalaya and west Assam witnessed heavy to very heavy with isolated extremely heavy rainfall. The synoptic conditions and the rainfall activity and the heavy rainfall warnings issued during this episode are discussed in the following sevtions.

3.5.2 Chief Synoptic Features during27th-30th June 2021

To find out the prevailing synoptic situations during the period, daily 00UTC and 03 UTC surface chartsand upper air data of 00UTC were analysed. GFS model analysis were also utilized to find out the circulation pattern and their vertical extension (Fig. 3.5.1-3). The east-west trough running either trough the NER or near to NER on the mean sea level was the major synoptic situations during 27-30 June. On 27th , a trough at mean sea level runs from North-West Uttar Pradesh to North-West Bay of Bengal across East Uttar Pradesh, South Jharkhand and North Odisha and on 28th , it was seen running from East Rajasthan to West Assam. On 29th and 30th, it was seen running from East Uttar Pradesh tonortheast Assam across Bihar and Sub-Himalayan West Bengal. In addition an upper air cyclonic circulation at north Chhattisgarh and its neighbourhood was present on 27th and 28th.

3.5.3 Monsoon activity Rainfall distribution and during the episode

During 28-30 June, the spatial distribution of rainfall over Assam–Meghalaya sub.division was either fairly wised spread or wide spread and the monsoon was active during the period (Table. 3.5.1).

Table 3.5.1 : Daily rainfall distribution and monsoon activity during 27th June – 01st July 2021 over Assam & Meghalaya.

Dates →	27/6	28/6	29/6	30/6	1/7
Rainfall Distribution	W	F	W	W	W
Monsoon Activity	N	A	A	A	N

F – Fairly Wide Spread, W – Wide Spread; N – Normal, A – Active

3.5.4 Districtwise rainfall distribution in Assam and Meghalaya

The observed rainfall over various districts of west Assam and Meghalaya during 28th June to 01st July 2021 is given in Table 3.5.3 respectively. It reveals that during the above period the most of the districts in west Assam comprising Baska, Barpeta, Chirang, Bongaigaon,Dhubri, Goalpara, Kokrajahar and Nalbari received excess rainfall on consecutive dates. Similar pattern is also observed in Meghalaya also.

Table 3.5.2 : Rainfall departure (%) in the districts of West Assam and Meghalaya during 28thJune – 01st July

DATE	28-Jun-21	29-Jun-21	30-Jun-21	01-Jul-21
ASSAM				
BAKSA	-51	117	401	-32
BARPETA	189	694	492	-32
BONGAIGAON	40	281	86	22
CHIRANG	394	574	478	-14
DHUBRI	-28	52	135	9
GOALPARA	-19	462	63	-69
KOKRAJHAR	345	237	149	-48
NALBARI	113	219	302	-40
MEGHALAYA				
WEST GARO HILLS	-35	84	479	118
WEST KHASI HILLS	-23	222	222	-29
EAST GARO HILLS	426	413	648	548
EAST KHASI HILLS	265	638	97	-71
JAINTIA HILLS	37	156	25	-69
SOUTH GARO HILLS	43	470	1542	573

During 28-30 June, several stations in west Assam and Meghalaya reported heavy to vey heavy rainfall and extremely rainfall was observed at one or two

stations. Iso-hytel maps during 28-30 June are presented in Fig. 3.5.4. Stationwise distribution of rainfall (>= 5cm)during on 28th to 30th June is presented in Table3.

Table 3.5.3 **:** Stationwise24 hours Rainfall (≥ 5cm) during 28-30 June 2021

Date	Stations of Assam and Meghlaya with R/F in cm
28-Jun-21	Mawsynram 33 Sohra 32 Sohra(RKM) 30 Manikpur (ARG) 14 Gossaigaon AGRI 13 Kokrajhar 12 Manas N H Xing 11 Roing 11 Panbari 10 Karimganj 8 Williamnagar 7 Khliehriat 7 Barpeta 6 Beki Rd. Bridge 5 Beki-Mathanguri 5 Nalbari 5
29-Jun-21	Sohra 56 Sohra (RKM) 55 Mawsynram 47 Manikpur (ARG) 22 Manas N H Xing 16 Barpeta 15 Beki Rd. Bridge 14 Nongstoin 13 Shella 12 Jowai 12 Panbari 11 Goalpara (CWC) 11 Goalpara 11 Baghmara 10 Gossaigaon AGRI 9 Khliehriat 9 Kokrajhar 7 Beki-Mathanguri 6 Williamnagar 6 Nalbari 5 Hazuwa 5 Aie N H Xing 5
30-Jun-21	Baghmara 28 Sohra(RKM) 23 Beki-Mathanguri 23 Mawsynram 23 Sohra 22 Panbari 17 Hazuwa 15 Tura KVK 15 Manikpur(ARG)14 Williamnagar 12 Beki Rd. Bridge 10 Barpeta 10 Manas N H Xing 10 Kokrajhar 9 Motunga 9 Shella 8Jowai 8 Gossaigaon AGRI 8 Dhubri 7 Nongstoin 6 Dhubri(CWC) 6 Khliehriat 6 Ampati 6 Tamulpur 6 Goibergaon 6 DRF 6 Tikrikilla 5 Goalpara(Cwc) 5

3.5.5 Causes of the Heavy Rainfall Activity

There were different diagnostic, prognostic and synoptic meteorological features which may be attributed as a possible explanation of this heavy to very heavy rainfall activity which occurred in Assam & Meghalaya. Synoptically, during this epoch the presence of an East-West trough was either passing through NER or was very close to NER dipping in the North Bay of Bengal. At the same time there was an upper air cyclonic circulation extended up to 3.1 km over North Chhattisgarh& neighborhood on 27th and 28th. Due to the simultaneous presence of these systems, strong wind confluence were seen over Western paerts of NER specially over west Assam and west Meghalaya. During the period strong Southerly/ South-westerly winds across Bangladesh were present in the lower levels of the atmosphere. Strong moisture flux converegence of the order of more than 500 kg/m/sc (Fig. 3.5.5) were also contributing largely to the enhaced rainfall activity during the period.

3.5.6 Weather Warnings issued by RMC Guwahati

The fundamental tools used in the analysis of this event to issue forecast and warning were analysis of various synoptic charts, guidance from various NWP model products enriched with Satellite and DWR products. The forecast, warnings and impact based forecast bulletins were generated after detailed analysis of these products and proper value addition to be close to the reality.

RMC Guwahati issues heavy rainfall warnings and advisories to various agencies including district administrators and disaster management authorities and the other end users of the region During the epoch of this heavy rainfall spell (28^{th} - 30^{th} June 2021), adverse weather warnings were issued for Assam & Meghalaya were as follows:

28^{h} June**:**Heavy to very heavy rain with extremely heavy falls is very likely to occur at isolated places over Assam & Meghalaya on 28th, 29th & 30th June'21.

29th June**:**Heavy to very heavy rain with extremely heavy falls is very likely to occur at isolated places over Assam & Meghalaya on 29th & 30th June'21.

30th June**:**Heavy to very heavy with extremely heavy rain is very likely to occur at isolated places over Assam & Meghalaya on 30th June 2021.

3.5.7 Conclusion

In the month of June 2021 during the period 28^{th}-30^{th}, fairly wide spread to wide spread rainfall occurred over Assam & Meghalaya heavy to very heavy rainfall at few places with isolated extremely heavy falls over West Assam and meghalaya. The meteorological conditions responsible for enhaced rainfall activity may primarily be attributed to the presence of Eeast-West troughon mean sea level passinf through northeastern states or near by. Simultaneously, a large scale moisture incursion due to strong South-Southwesterly winds in lower and mid tropospheric levels leading to this enhancedheavy rainfall episode.

3.5.8 Acknowledgement

The authors are thankful to the Director General of Meteorology for his continuous encouragement and support extended for this article. The NWP model outputs were provided by the NWP Division, IMD New Delhi.

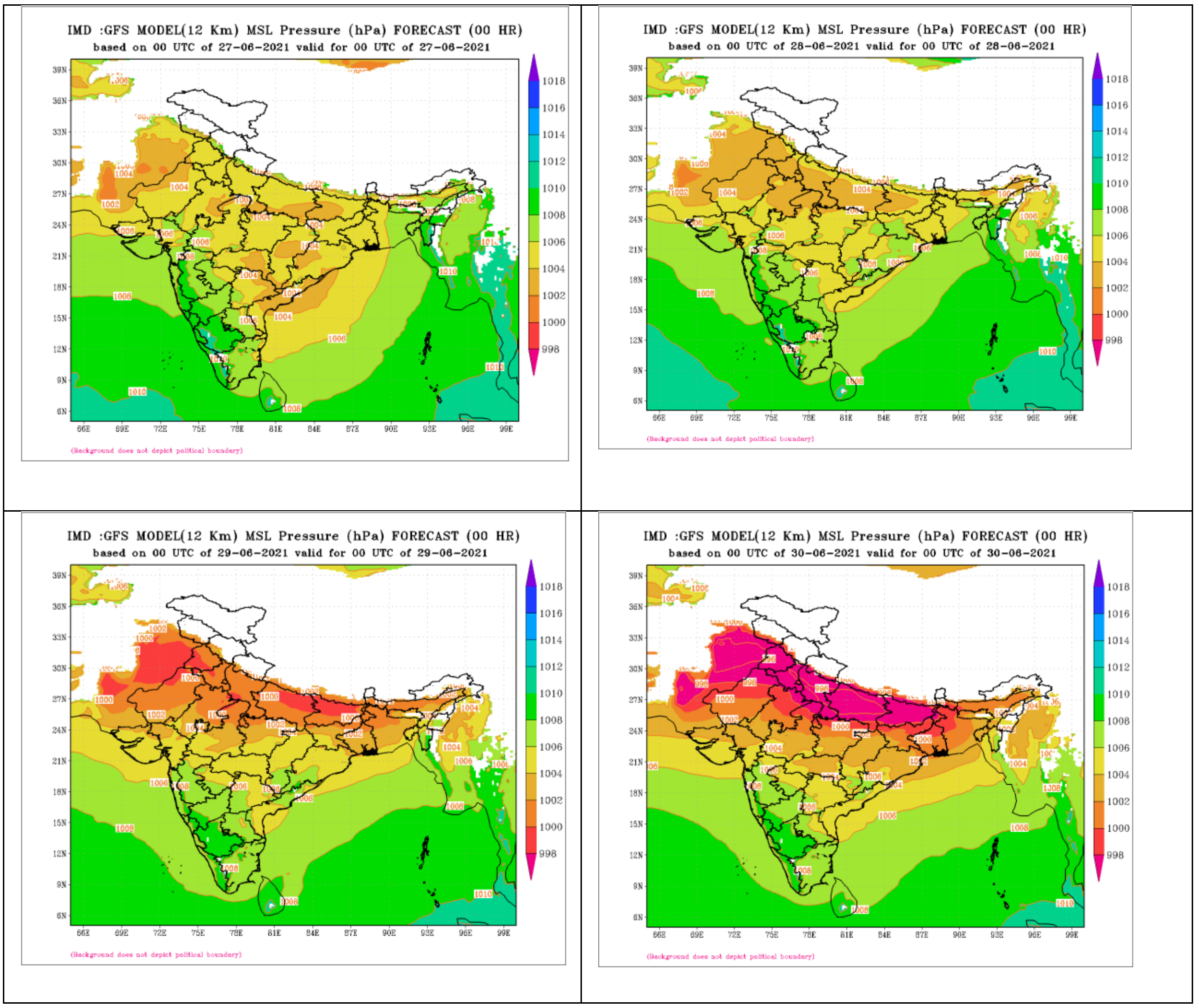


Fig. 3.5.1 : GFS analysis of 0000UTC surface charts 27-30 June 2021

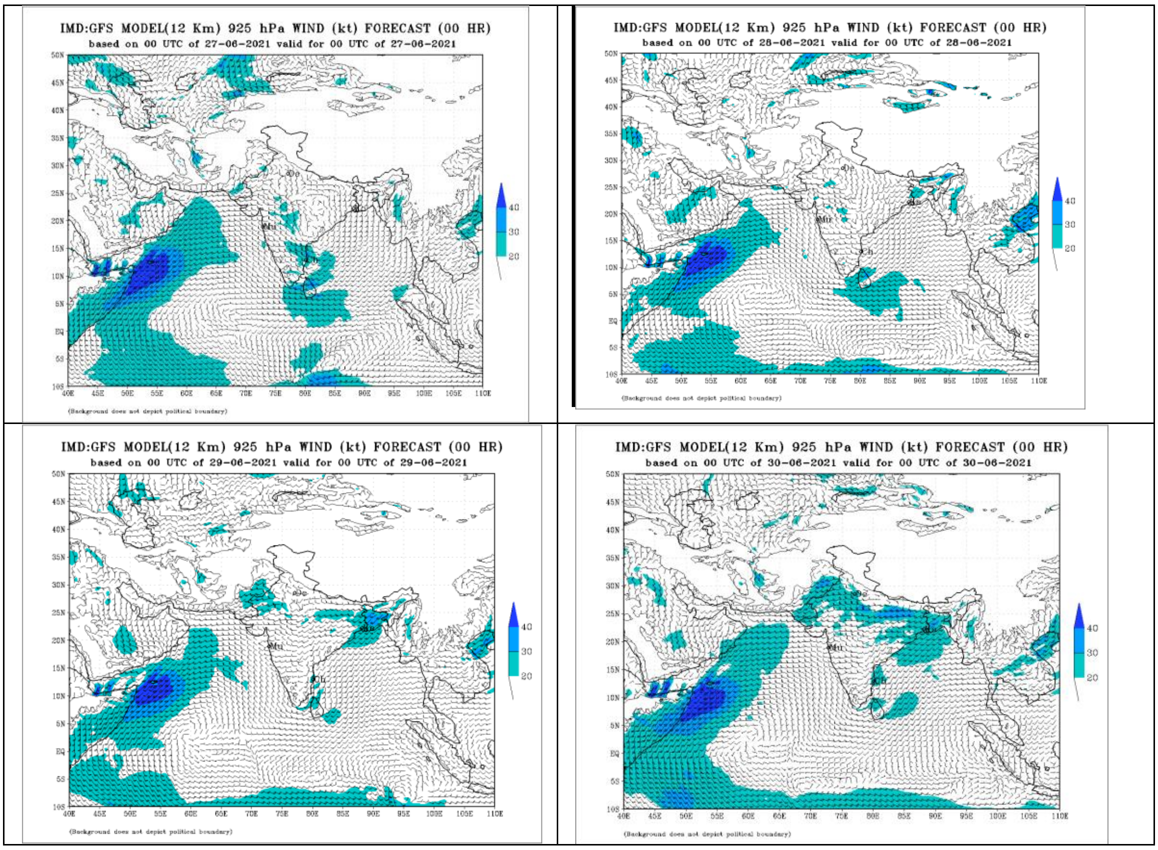


Fig. 3.5.2 : GFS analysis of 925 hPa winds (00 UTC) during 27-30 June 2021

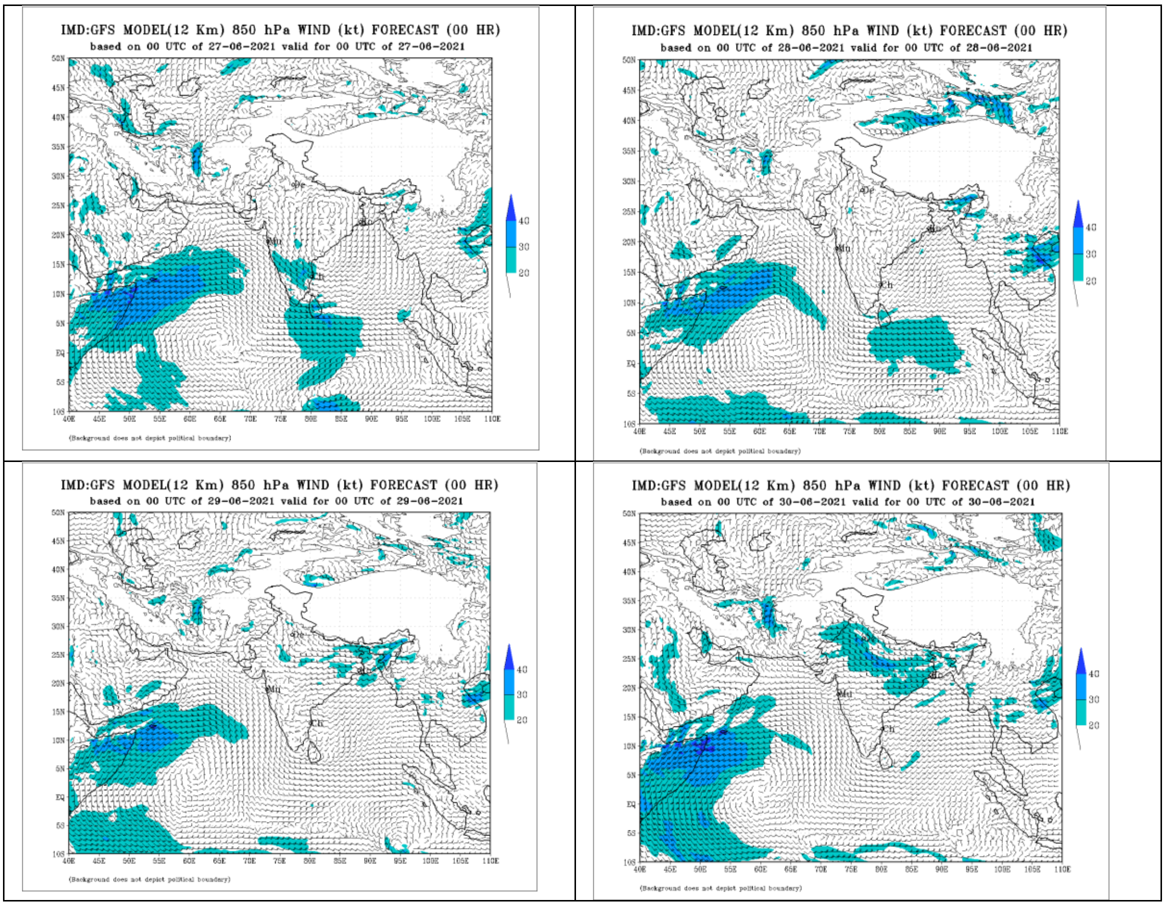


Fig. 3.5.3 : GFS analysis of 850hPa winds (00 UTC) during 27-30 June 2021

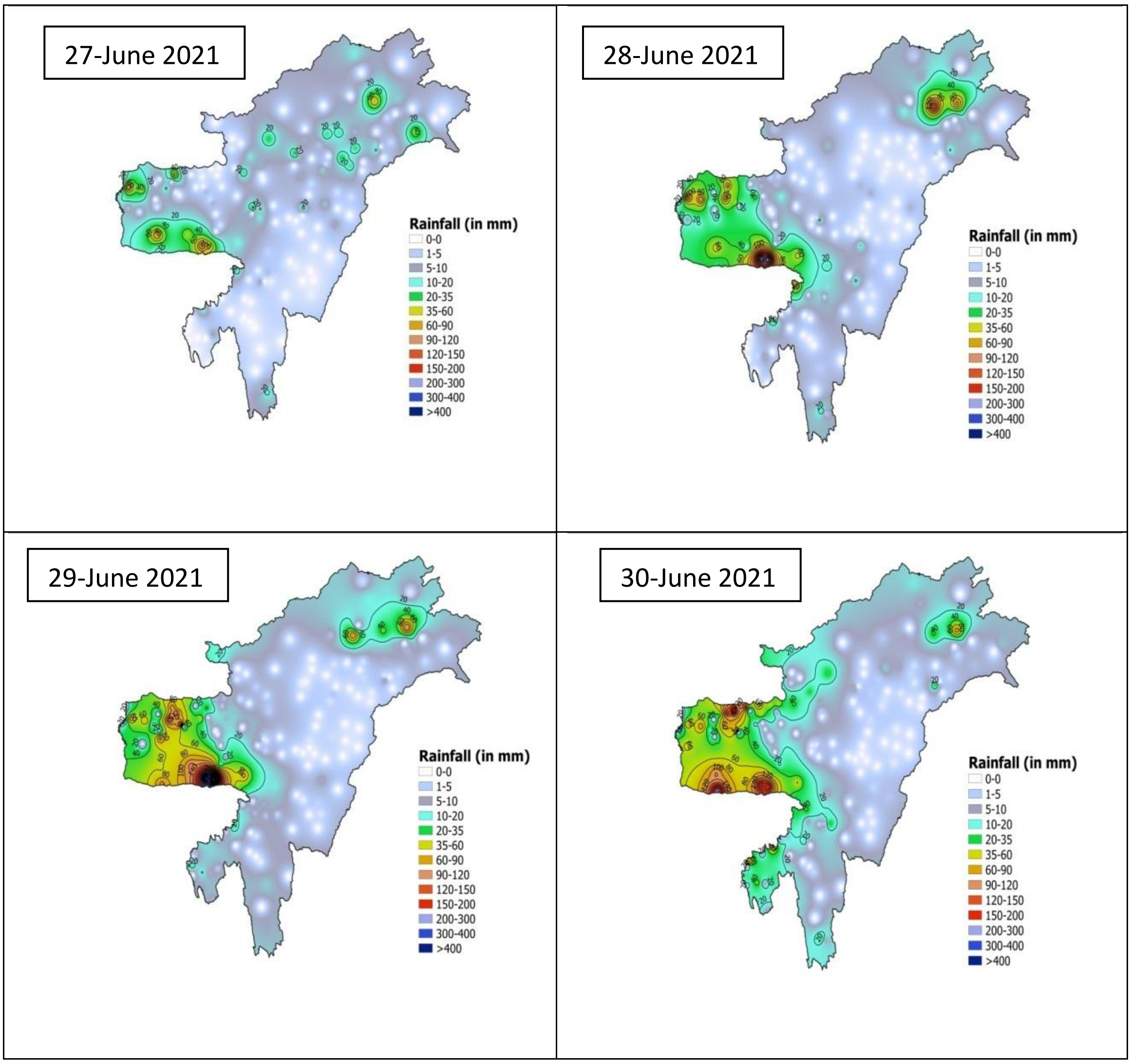


Fig. 3.5.4 : Isohytel map of daily rainfall during 27-30 June 2021

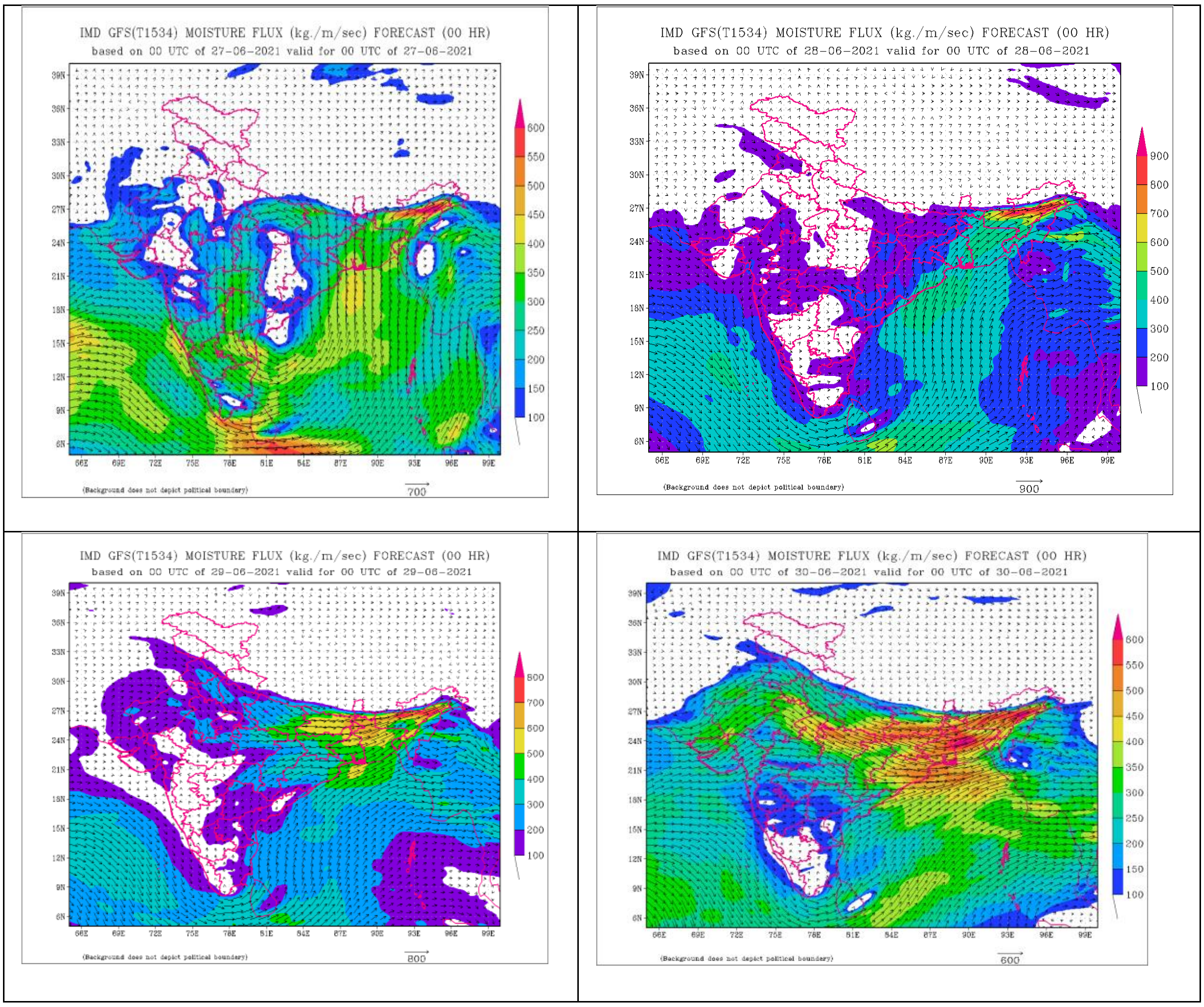


Fig. 3.5.5 : GFS Moisture Flux (kg/m/sc) at (00 UTC) during 27-30 June 2021

3.6

EXTREMELY HEAVY RAINFALL OCCURRENCES OVER THE SOUTHERN PENINSULAR REGION

B. Geetha, S. Balachandran, K. Santosh, S. Stella, Geeta Agnihotri and K. Nagaratna

The southern peninsular (SP) region comprising of the nine meteorological subdivisions of Kerala &Mahe (KER), Lakshadweep (LAK), Coastal Karnataka (CK), South Interior Karnataka (SIK), North Interior Karnataka (NIK), Telangana (TEL), Coastal Andhra Pradesh &Yanam (CAP), Rayalaseema (RYS) and Tamil Nadu, Puducherry &Karaikal (TN) experience *heavy rainfall* events (≥ 7 cm/day) under the influences of monsoon lows / depressions / other synoptic scale low pressure systems / off shore troughs & vortices / troughs in monsoon westerlies etc. During the period June-September (JJAS), 2021, the number of days of *heavy rainfall* reports over each of these subdivisions as per the classifications of *heavy rainfall* by the India Meteorological Department (IMD) is presented in Table-3.6.1.

Table-3.6.1 : Number of days of heavy rainfall occurrences over various subdivisions in the southern region during June-September 2021

No. of days of heavy rainfall occurrences															
Sub Div	**JUN**			**JUL**			**AUG**			**SEP**			**JUN-SEP**		
	H	**VH**	**XH**	**H**	**VH**	**XH**	**H**	**VH**	**XH**	**H**	**VH**	**XH**	**H**	**VH**	**XH**
KER	14	5	0	16	7	0	12	3	0	11	1	0	53	16	0
LAK	1	0	0	0	0	0	1	0	0	0	0	0	2	0	0
CK	10	1	0	22	15	2	10	4	0	14	3	0	56	23	2
SIK	15	7	2	22	10	2	16	5	0	16	6	0	69	28	4
NIK	10	3	0	10	2	1	4	0	0	8	1	0	32	6	1
TEL	15	7	0	18	10	3	15	3	0	19	7	2	67	27	5
CAP	7	0	0	16	2	0	14	1	0	12	6	1	49	9	1
RYS	7	2	0	11	2	1	2	0	0	10	1	0	30	5	1
TN	15	6	2	22	4	0	16	2	0	20	8	0	73	20	2

Legend: H: Heavy rain (≥ 7 cm (64.5 mm)/day);VH: Very Heavy rain (≥ 12 cm (115.6 mm) /day);XH: Extremely Heavy rain (≥ 21cm (204.5 mm) /day).

It is observed that TN experienced 73 days of isolated heavy rain (including 20 days of isolated very heavy(VH) rainfall (≥ 12 cm/day) reports with 2 days of extremely heavy(XH) rainfall (≥ 21cm/day) events at one or two places) followed by SIK & TEL with 69 and 67 days of heavy rainfall reports. CK, SIK, TEL & TN experienced isolated very heavy rainfall activity on more than 20 days during the season (23, 28, 27 & 20 days respectively). KER experienced 16 days of isolated very heavy rainfall activity and CAP, RYS & NIK experienced less than 10 days of isolated very heavy rainfall activity. Extremely heavy rainfall events occurred over TEL on 5 days, over SIK on 4 days, over CK & TN on 2 days each and over NIK, CAP & RYS on 1 day each. There were no extremely heavy rainfall occurrences over KER & LAK during the season.

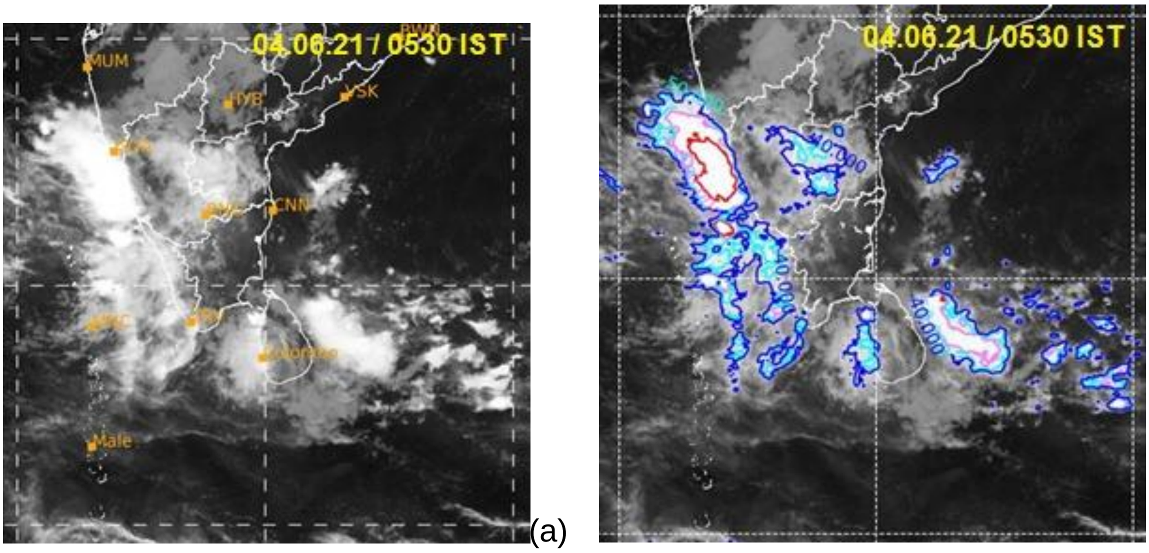
Wankdi (KumaramBheem district) in TEL recorded the highest rainfall amount of 387.2 mm (23rd July) followed by 385.3 mm recorded at Mulki (Dakshin Kannada district) in CK (04th June) in the southern region during the period June-September 2021.

In CK, aside from Dakshin Kannada (Mulki, 04th June), Uttara Kannada also recorded XH rainfall on 18th and 23rd July. In SIK, XH rain was recorded in Shivamogga district on 17th& 18th June and 15th& 23rd July; Chikkamagaluru district – 17th June & Kodagu district – 18th June. On 23rd July, Belagavi district in NIK also recorded XH rain.In TEL, aside from KumaramBheem on 23rd July, Medak (15th July), Nirmal (22nd& 23rd July), Adilabad (22nd July), Warangal rural (07th September) and Nizamabad (28th September) also recorded XH rainfall during the season. In CAP, Visakhapatnam and Vizianagaram districts recorded XH rainfall on 27th September. Isolated XH rainfall was also recorded in RYS, Anantapur district (18th July) and in TN, Nilgiris district (17th& 18th June) during the season.

The list of extremely heavy rainfall events over the southern region during June-September 2021 is presented in Table-3.6.2.

A brief description of synoptic features associated with these extremely heavy rainfall events is furnished below:

(i) The XH rainfall event over CK, Dakshin Kannada reported on 04th June was during the onset phase of the monsoon and in association with offshore trough at mean sea level and cyclonic circulation over eastcentral Arabian sea off Karnataka coast in the lower troposphere on 03rd June. Satellite imagery (INSAT-3D, TIR1, 04.06.21 / 0530 IST) depicting the cloudiness and INSAT-3D, TIR1 based cloud top brightness temperature (CTBT) indicating the vertical extension of clouds upto upper tropospheric levels (CTBT:-80°C) are shown in Fig.1(a&b).



(a) (b)

Fig.3.6.1 : (a) INSAT-3D, TIR1 imagery & (b) INSAT-3D, TIR1 based CTBT product as on 04.06.21 / 0530 IST

Table-3.6.2: List of extremely heavy rainfall events (as on 24-hr ending 8:30 IST of date) in the southern region during Jun-Sep 2021

Subdivision	Date	District, Station & Rainfall amount (mm)
CK	04Jun	Dakshin Kannada: Mulki-385.3
	18 Jul	Uttara Kannada: Bhatkal-209.0
	23Jul	Uttara Kannada: Janmane-343.0, Kadra-336.6, Banavasi-280.0, Siddapur -235.8, Yellapur-225.6, Haliyal-212.2, Manchikere-208.0
SIK	17Jun	Shivamogga: Hosanagar-320.8, Chikkamagaluru: Kottigehara-219.6
	18Jun	Shivamogga: Linganamakki HMS-217.2; Kodagu: Bhagamandala-207.4
	15 Jul	Shivamogga: Hosanagar-210.2
	23 Jul	Shivamogga: Thalaguppa- 267.4, Anavatti-244.2, AgaraharaKonanduru – 231.5, Sagar – 228.6
NIK	23 Jul	Belagavi: Londa-378.0, Khanapur- 270.2, Belagavi PTO – 207.8
TEL	15 Jul	Medak: Chegunta-207.6

	22 Jul	Nirmal: Dilawarpur-234.4, Sarangapur-218.2; Adilabad: Boath-211.4
	23 Jul	KumaramBheem: Wankdi-387.2, Asifabad-300.6; Nirmal: Sarangapur-204.6
	07 Sep	Warangal rural: Nallabelly-258.0, Khanapur-227.0, Parkal-204.6; Karimnagar: Huzurabad-253.4, Jammikunta-215.2; B Kothagudem: Kuthagudem-235.2; J Bhupalpally: Mugullapalle-235.2; Peddapalle: Dharmaram-222.0; RajannaSircilla: Konaraopeta- 206.6
	28 Sep	Nizamabad: Jakranpalle-225.8, Navipet-210.2, Dharpalle-209.4
CAP	27 Sep	Visakhapatnam: Visakhapatnam-282.4, Visakhapatnam AP-267.0; Vizianagaram: Gajapathinagaram-280.8, Nellimarla-278.0, Mentada-246.8, Pasupatirega- 239.2
RYS	18 Jul	Anantapur: Kadiri AWS-233, Kadiri-215.4
TN	17 Jun	Nilgiris: Avalanche-207.0
	18 Jun	Nilgiris: Upper Bhavani-216.0

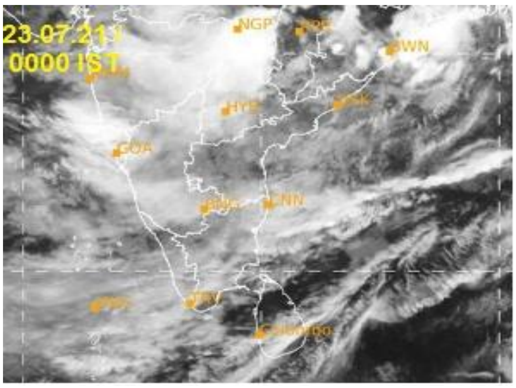
(ii) Under active monsoon conditions over the SIK, XH rainfall activity occurred over the western ghat areas (Shivamogga, Chikkamagaluru and Kodagu districts) which extended in to adjoining hilly areas of Tamil Nadu (Nilgiris district) on 17^{th}& 18^{th} June.

(iii) Under the influence of cyclonic circulation over south Chhattisgarh and neighbourhood tilting southwestwards with height and east-west shear zone roughly along 19°N latitude extending up to upper troposphere tilting southwards with height, XH rainfall occurred at isolated palces over SIK and TEL on 15^{th} July.

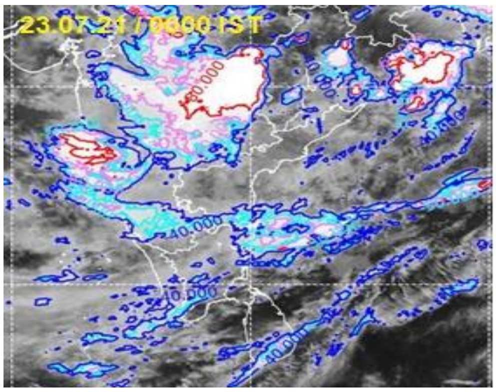
(iv) On 18^{th} July, under the influence of offshore trough at mean sea level off Maharashtra – Karnataka coastisoalted XH rainfall was reported over CK and under the influence of cyclonic circulation over north CAP and neighbourhood in the lower levels and east-west shear zone along 17°N latitude in the lower-mid troposphere tilting southwards with height, isolated XH rain was reported over RYS.

(v) Under the influence of (a) formation of a low pressure area over northwest Bay of Bengal and neighbourhood with associated cyclonic circulation extending upto upper tropospheric levels and (b) offshore trough at mean sea level off Maharashtra coast – north Kerala coast, XH rainfall was reported over TEL on 22nd& 23rd July and over NIK, SIK & CK on 23rd July. On 23rd, there were 23, 31 & 22 heavy rainfall reports over CK, SIK & NIK respectively which included 11, 20 & 10 VH with 7, 4 & 3 XH rainfall events respectively. Over TEL, there were 102 heavy rainfall reports including 41 VH with 3 XH rainfall events on the same day. The spatial rainfall distribution depicting this feature over CK, SIK, NIK (Karnataka state) & TEL and the associated satellite imagery (INSAT-3D, TIR1, 23.07.21 / 0000 IST) and the corresponding CTBT product depicting the intense cloudiness over the region (CTBT:-80°C) are shown in Fig.3.6.2(a-c).

(vi) Under the influence of a well marked low pressure area over south Chhattisgarh and adjoining south Odisha with associated cyclonic circulation extending upto upper troposphere tilting southwestwards with height and an east-west shear zone roughly along 18°N latitude extending upto upper tropospheric levels tilting southwards with height across the cyclonic circulation associated with the well marked low pressure area, XH rainfall was reported over Telangana on 07th September. In fact, there were 117 heavy rainfall reports including 58 VH with 9 XH rainfall events over TEL on that day. The spatial rainfall distribution depicting this feature and associated satellite imagery (INSAT-3D, TIR1, 06.09.21 / 1930 IST) and the corresponding CTBT product depicting the intense cloudiness over the region (CTBT:-80°C) are shown in Fig.3.6.3(a-c). Associated with this intense rainfall event, inland flooding was reported in the media (Fig.3.6.3d).



(a)



(b)

Fig.3.6.2 : (a) INSAT-3D, TIR1 imagery & (b) INSAT-3D, TIR1 based CTBT product as on 23.07.21/ 0000 IST

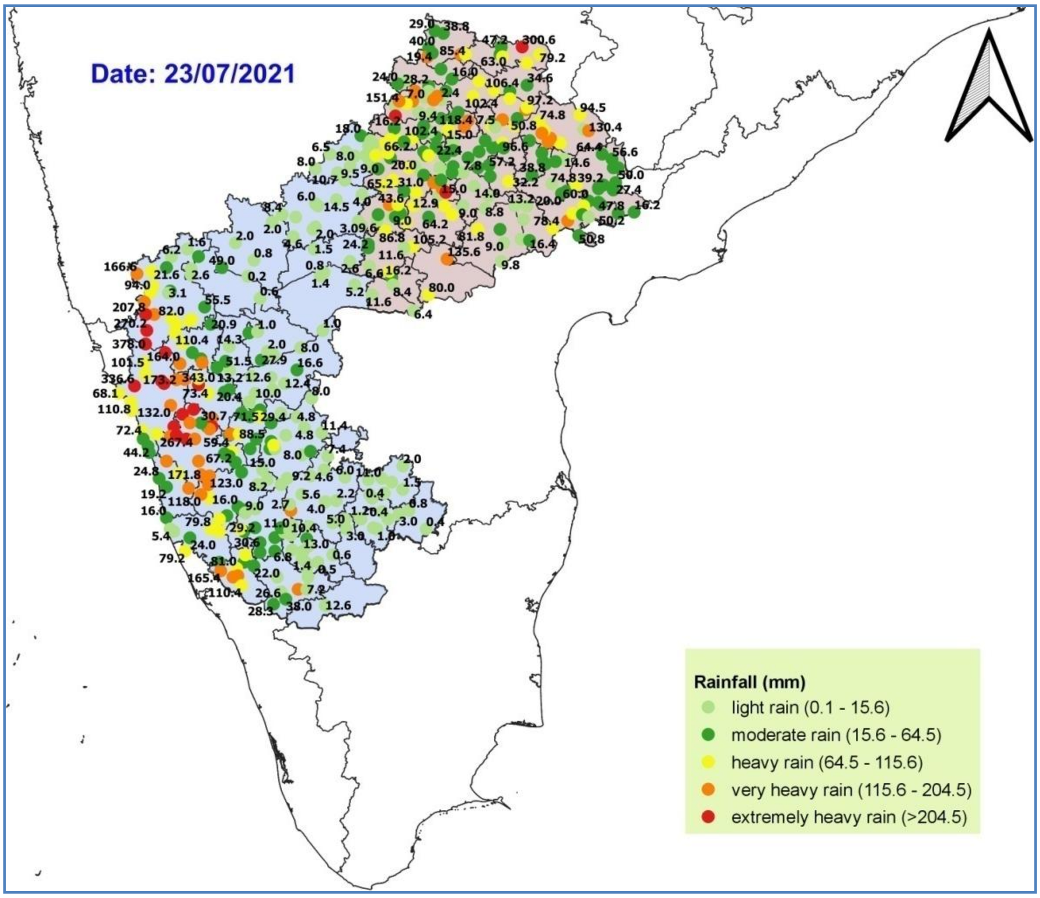
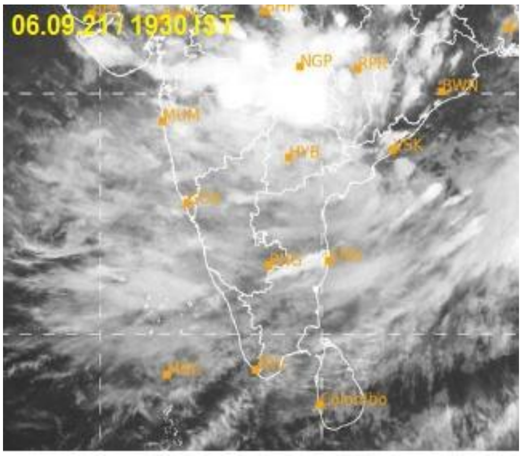
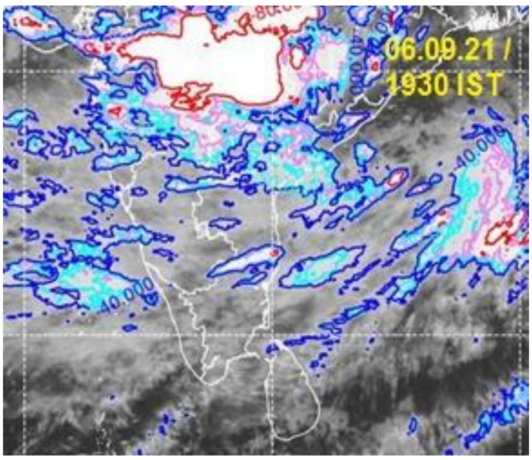


Fig. 3.6.2c : Spatial distribution of past 24-hr rainfall over Karnataka (CK, SIK & NIK) and Telangana as on 23.07.21/08:30 IST

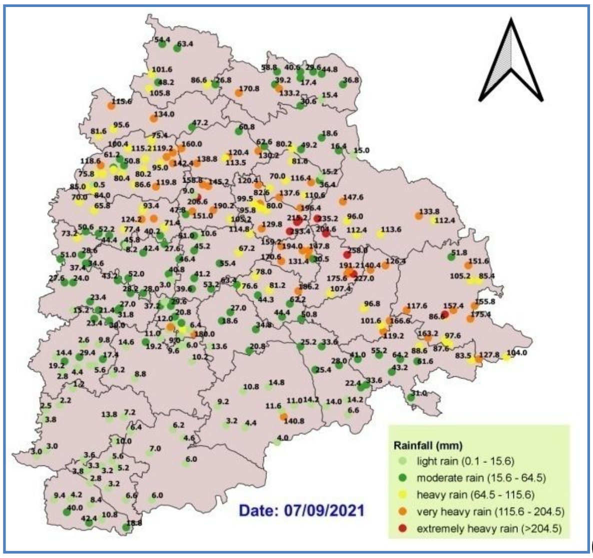


(a)



(b)

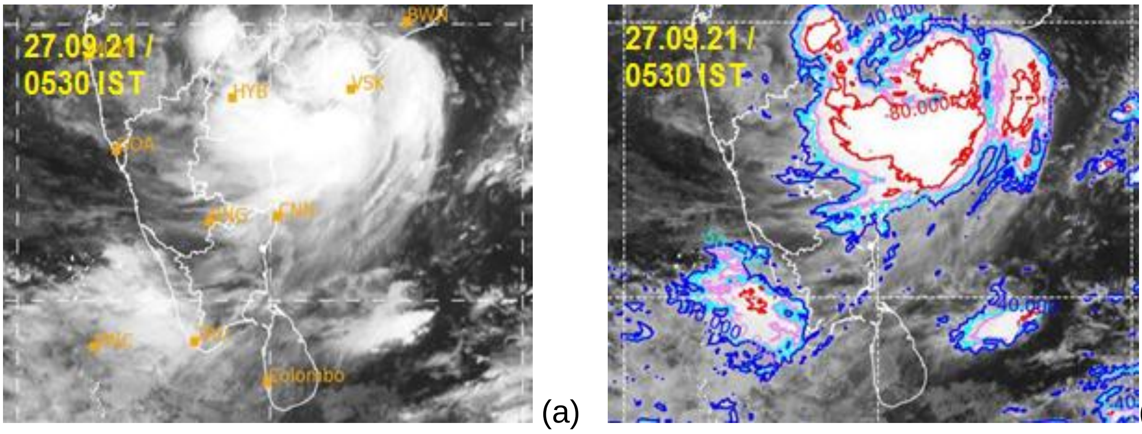
Fig.3.6.3 : (a) INSAT-3D, TIR1 imagery & (b) INSAT-3D, TIR1 based CTBT product as on 06.09.21 / 1930 IST



(c)

Fig.3.6.3 : (c) Spatial distribution of past 24-hr rainfall over Telangana as on 07.09.21/08:30 IST.

(vii) Under the influence of cyclonic storm **Gulab** that formed over the Bay of Bengal and crossed coast over north Andhra Pradesh – south Odisha coast on the evening of 26th September and its further westward movement, XH rainfall was reported over Visakhapatnam and Vizianagaram districts of CAP on 27th and over TEL on 28th. The spatial rainfall distribution depicting the rainfall feature and associated satellite imagery (INSAT-3D, TIR1, 27.09.21 / 0530 IST) depicting the cloudiness and the corresponding CTBT indicating the vertical extension of clouds up to upper tropospheric levels (CTBT:-80°C) are shown in Fig.4(a-c).



(a) (b)

Fig.3.6.4 : (a) INSAT-3D, TIR1 imagery & (b) INSAT-3D, TIR1 based CTBT product as on 27.09.21 / 0530 IST

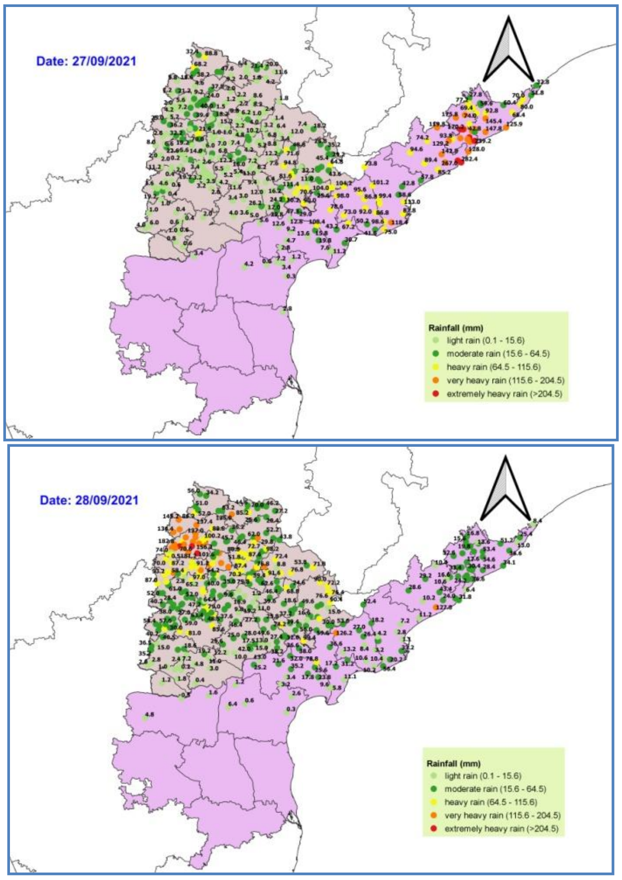


Fig.3.6.4c : Spatial distribution of past 24-hr rainfall over CAP and Telangana as on 08:30 IST of 27.09.21 and 28.09.21

Summary : During the period June-September 2021, associated with offshore trough, upper air circulations, formation of low pressure area, east-west shear zone and passage of cyclonic storm ‘Gulab’ and under orographic influence, extremely heavy rainfall occurred on five days over Telangana, four days over South Interior Karnataka, two days each over CK & TN and one day each over NIK, CAP & RYS. Wankdi (KumaramBheem district) in TEL recorded the highest rainfall amount of 387.2 mm over the southern region on 23rd July. Associated with these intense rainfall events, water logging and inland flooding in some areas were reported by the media.

4

RAINFALL FEATURES

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(In this chapter, various spatial and temporal features of rainfall during the season and its statistics have been discussed.)

The Southwest Monsoon season rainfall over the country as a whole during 2021 was 99.3 % of Long Period Average (LPA).Rainfall distribution was generally fairly well distributed over major parts of the countryexcept Arunachal Pradesh, Assam & Meghalaya, Nagaland, Manipur, Mizoram and Tripura, West Uttar Pradesh, Jammu & Kashmir and Ladakh and Lakshadweep sub-division. The season observed significant intra seasonal variationsin rainfall as realized rainfall in September (135.1 % of LPA)being above normal,June (109.6 % of LPA) &July (93.2 % of LPA)being normal and August (76 % of LPA) being below normal.

4.1 General Features (Rainfall):

For the country as a whole, seasonal rainfall at the end of the southwest monsoon season (June to September) was 99.3% of its LPA value.For the country as a whole, the LPA value of southwest monsoon season rainfall, based on the data for the period 1961- 2010 is 880.6mm.

The four homogeneous regions received seasonal rainfall as follows:

i. East & Northeast India -88.4 % of LPA
ii. Northwest India - 96.1% of LPA
iii. South Peninsula - 110.7% of LPA
iv. Central India - 103.7% of LPA

The country received monthly rainfall during the season asfollows:

i. June-109.6% of its LPA
ii. July-93.2 % of its LPA
iii. August-76 % of its LPA
iv. September -135.1 %of its LPA

During the season, out of 36 meteorological subdivisions, ten subdivisions (Andaman & Nicobar Islands, Gangetic West Bengal, Haryana, Chandigarh and Delhi, West Rajasthan, Surashtra& Kutch, Konkan & Goa, Marathwada, Coastal Andhra Pradesh, Telangana and North Interior Karnataka) received excess, twenty subdivisions (Sub-Himalayan West Bengal & Sikkim, Orissa, Jharkhand, Bihar, East Uttar Pradesh, Uttaranchal, Punjab, Himachal Pradesh, East Rajasthan, West Madhya Pradesh, East Madhya Pradesh, Gujarat Region, Madhya Maharashtra, Vidarbha, Chhattisgarh, Rayalaseema, Tamil Nadu, Coastal Karnataka, South Interior Karnataka and Kerala) received normal and six subdivisions (Arunachal Pradesh, Assam & Meghalaya, Nagaland, Manipur, Mizoram and Tripura, West Uttar Pradesh, Jammu & Kashmir and Ladakh and Lakshadweep) received deficient rainfall (Fig 4.1).

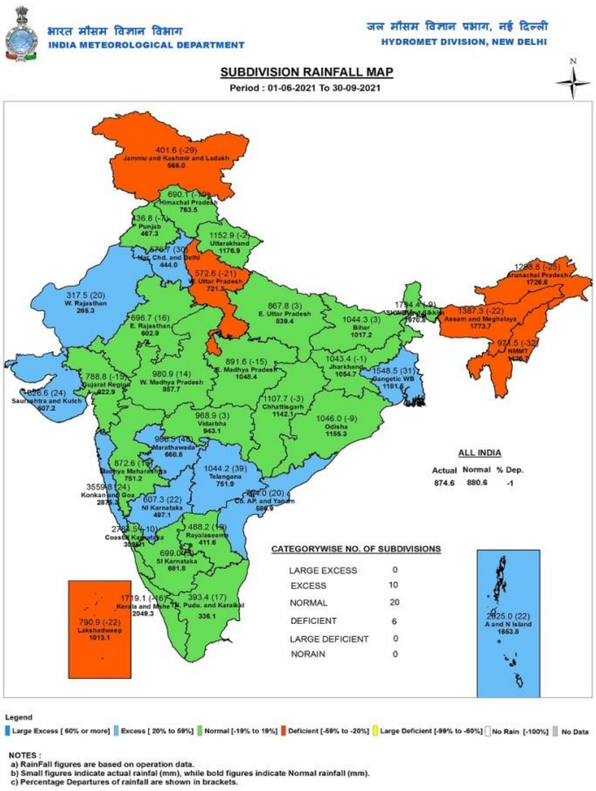


Fig.4.1: Sub-division wiseSW monsoon rainfall distribution (% departure).

Fig.4.2 shows the number of sub-divisions receiving deficient (-20% to -59%) and Large deficient (-60% to -99%) rainfall during the southwest monsoon season during the last ten years.

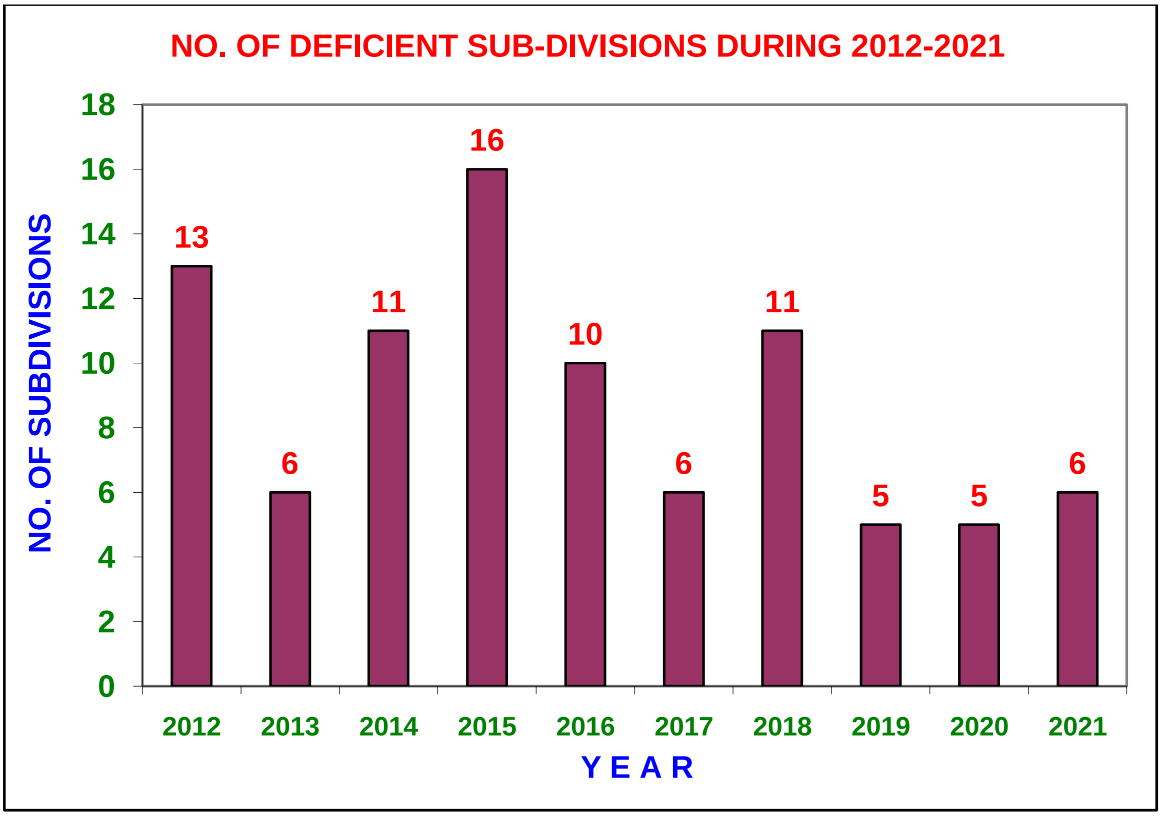


Fig.4.2: Number of sub-divisions receiving deficient and large deficient rainfall during the last 10 years.

Fig.4.3 shows the district wise rainfall distribution during the southwest monsoon season over the country. During the season, out of 685 districtsfor which data were available, 59districts received largeexcess rainfall, 164 districts receivedexcess rainfall, 290 districts received normal rainfall, 155 districts received deficient rainfall and 17 districts received large deficient rainfall. Percentage of districts with large excess/excess/normal and deficient/large deficient rainfall for the years 2010-2020 is given in the table 9.1 below:

Table-4.1:Percentage of districts with large excess/excess/normal and deficient/large deficient rainfall for the years 2010-2020

Year	Large Excess, Excess&Normal	Deficient&Large Deficient
2010	70	30
2011	76	24
2012	58	42
2013	73	27
2014	54	46
2015	51	49
2016	68	32
2017	67	33
2018	61	39
2019	77	23
2020	75	25

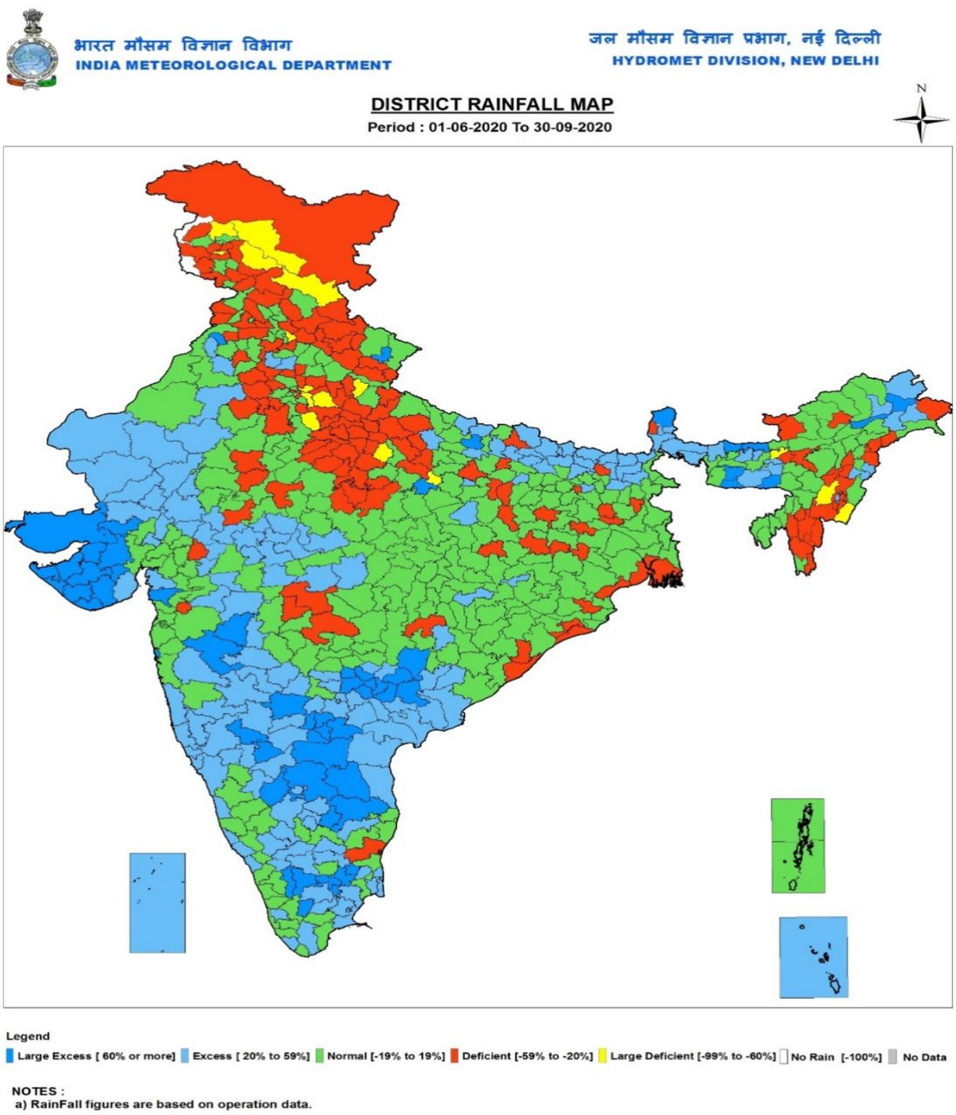


Fig.4.3: District wise monsoon rainfall distribution (% departure).

4.2 Monthly rainfall distribution:

4.2.1 Meteorological Sub-division wise monthly distribution of rainfall:

June:

During the month, rainfall activity over the country as a whole was109.6% of LPA.During the month, except 8 subdivisions (Arunachal Pradesh, Nagaland, Manipur, Mizoram & Tripura, Jammu & Kashmir and Ladakh, Saurashtra & Kutch, Coastal Andhra Pradesh &Yanam, Kerala &Mahe and both the islands) all other subdivisions received large excess/excess/normal rainfall. Rainfall received over the subdivisions of Bihar, east Uttar Pradesh, Telangana, Rayalaseema and North Interior Karnataka was one and half times of its normal value. Out of 36 meteorological subdivisions, 3 received large excess rainfall, 13 received excess rainfall, 12 subdivisions received normal rainfall and 8 subdivisions received deficient rainfall(Fig.4.4a).

July:

During the month, rainfall activity over the country as a whole was 93.2 % of LPA. Except most of the sub-divisions in the east and northeast India, West Rajasthan, Gujarat state, Kerala &Mahe and Lakshadweep remaining subdivisions received large excess/excess/normal rainfall. Rainfall over Haryana, Chandigarh & Delhi, Telangana, Rayalaseema, Tamilnadu, Puducherry &Karaikal and North Interior Karnataka was more than 1.5 times of its normal value. Rainfall deficiency over Arunachal Pradesh, Assam & Meghalaya, Nagaland, Manipur, Mizoram & Tripura, Gujarat state, and Lakshadweep island was more than 30%. Out of 36 meteorological subdivisions, 3 received large excess rainfall, 9 received excess rainfall, 11 received normal rainfall and 13 subdivisions received deficient rainfall(Fig.4.4b).

August:

During the month, rainfall activity over the country as a whole was 76 % of LPA. During the month, subdivisions from north, east-central India, Nagaland, Manipur, Mizoram & Tripura. Gujarat state, Konkan & Goa, Madhya Maharashtra and Coastal Karnataka received deficient/large deficient rainfall. Remaining 18 subdivisions received excess/normal rainfall. Rainfall deficiency over Punjab, Jammu & Kashmir and Ladakh, West Rajasthan and Gujarat state was more than -50%. Out of 36 meteorological subdivisions, 4 received excess rainfall, 14 subdivisions received normal rainfall and 18 subdivisions received deficient/large deficient rainfall (Fig 4.4c)

September:

During the month, rainfall activity over the country as a whole was135.1 % of LPA.During the month, most of the subdivisions received large excess/excess/normal rainfall except some subdivisions from east & northeast India, Jammu & Kashmir and Ladakh, Rayalaseema and South Interior Karnataka. Sub divisions like Haryana, Chandigarh & Delhi, Rajasthan state, Gujarat state, Konkan & Goa and Marathwada received twice the normal rainfall. Out of 36 meteorological subdivisions, 14 subdivisions received large excess rainfall, 6 received excess rainfall, 8 subdivisions received normal rainfall and 8 subdivisions received deficient/large deficient rainfall (Fig.4.4d).

Monthly and seasonal sub-division wise rainfall statistics for the 2021 monsoon season are given in the Table-4.2.

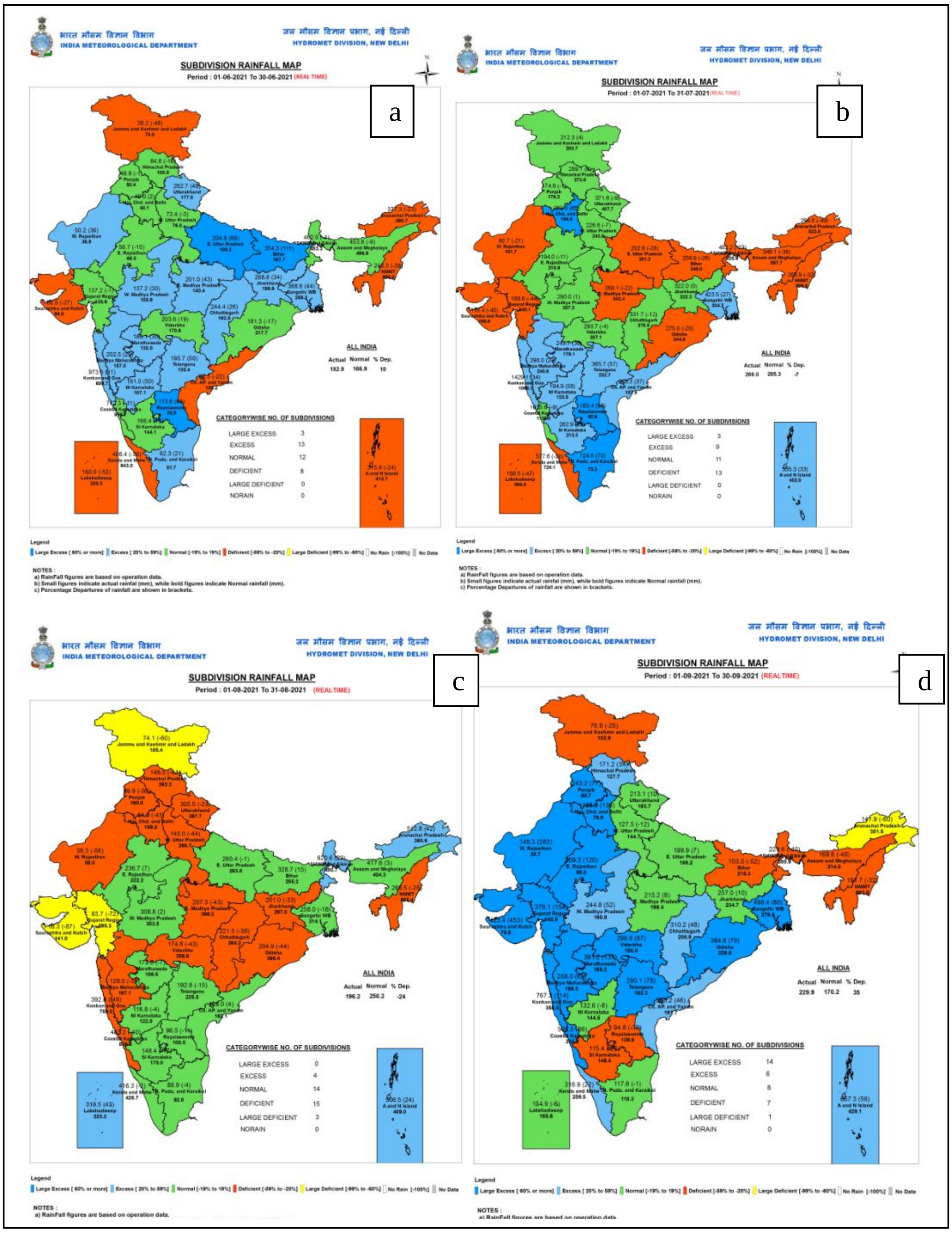


Fig.4.4(a-d): Monthly sub-division wise rainfall departure for JJAS 2021.

Table-4.2: Monthly and seasonal sub-division wise rainfall statistics for the 2021southwestmonsoon season

S. NO.	METEOROLOGICAL SUBDIVISIONS	JUNE			JULY			AUGUST			SEPTEMBER			SW MONSOON		
		ACTUAL	NORMAL	% DEP.	ACTUAL	NORMAL	% DEP.	ACTUAL	NORMAL	% DEP.	ACTUAL	NORMAL	% DEP.	ACTUAL	NORMAL	% DEP.
1	A & N ISLAND	315.9	413.7	-24	535.3	402.0	33	506.5	409.0	24	667.3	429.1	56	2025.0	1653.8	22
2.	ARUNACHAL PRADESH	377.3	490.7	-23	266.8	523.8	-49	512.8	360.6	42	141.9	351.5	-60	1298.8	1726.6	-25
3.	ASSAM & MEGHALAYA	453.8	496.9	-9	346.1	557.7	-38	417.6	404.3	3	169.6	314.8	-46	1387.3	1773.7	-22
4.	N M M T	246.3	398.0	-38	265.9	389.5	-32	266.5	355.4	-25	191.7	283.8	-32	971.5	1426.7	-32
5.	SHWB & SIKKIM	462.0	483.3	-4	482.2	625.9	-23	620.6	480.7	29	229.6	380.9	-40	1794.4	1970.8	-9
6.	GANGETIC WEST BENGAL	368.6	256.2	44	423.5	334.7	27	258.0	314.1	-18	498.4	276.5	80	1548.5	1181.5	31
7.	ODISHA	181.3	217.7	-17	275.0	344.6	-20	204.9	366.4	-44	384.8	226.6	70	1046.0	1155.3	-9
8.	JHARKHAND	268.6	199.9	34	322.0	322.3	0	201.0	297.8	-33	257.0	234.7	10	1043.4	1054.7	-1
9.	BIHAR	354.3	167.7	111	258.9	349.0	-26	328.7	285.2	15	103.0	215.3	-52	1044.3	1017.2	3
10.	EAST U.P.	204.9	108.2	89	202.8	281.2	-28	260.4	263.8	-1.3	199.9	186.2	7	867.8	839.4	3
11.	WEST U.P.	73.4	76.0	-3	226.6	243.9	-7	145.0	256.7	-44	127.5	144.7	-12	572.6	721.3	-21
12.	UTTARAKHAND	262.7	177.8	48	371.6	407.7	-9	305.5	397.7	-23	213.1	193.7	10	1152.9	1176.9	-2
13.	HAR. CHD & DELHI	49.0	48.1	2	259.0	156.8	65	84.5	159.2	-47	188.9	79.9	136	576.7	444.0	30
14.	PUNJAB	49.9	50.4	-1	174.9	176.2	-1	69.9	160.0	-56	143.2	80.7	77	436.8	467.3	-7
15.	HIMACHAL PRADESH	84.6	100.5	-16	289.1	273.0	6	146.5	262.3	-44	171.2	127.7	34	690.1	763.5	-10
16.	JAMMU & KASHMIR& LADAKH	38.2	74.0	-48	212.3	203.7	4	74.1	185.4	-60	76.9	102.9	-25	401.6	566.0	-29
17.	WEST RAJASTHAN	50.2	36.9	36	80.7	101.7	-21	38.3	88.0	-56	148.3	38.7	283	317.5	265.3	20
18.	EAST RAJASTHAN	56.7	66.8	-15	194.0	218.9	-11	236.7	222.2	7	209.3	95.0	120	696.7	602.9	16
19.	WEST MADHYA PRADESH	137.2	105.9	30	290.0	287.2	1	308.8	303.8	2	244.8	160.8	52	980.9	857.7	14
20.	EAST MADHYA PRADESH	201.0	140.4	43	268.1	342.4	-22	207.3	366.2	-43	215.2	199.4	8	891.6	1048.4	-15

S. NO.	METEOROLOGICAL SUBDIVISIONS	JUNE			JULY			AUGUST			SEPTEMBER			SW MONSOON		
		ACTUAL	NORMAL	% DEP.	ACTUAL	NORMAL	% DEP.	ACTUAL	NORMAL	% DEP.	ACTUAL	NORMAL	% DEP.	ACTUAL	NORMAL	% DEP.
21.	GUJARAT REGION	137.2	138.6	-1	189.8	340.1	-44	83.7	295.3	-72	378.1	148.9	154	788.8	922.9	-15
22.	SAURASHTRA & KUTCH	68.5	94.0	-27	116.4	195.6	-40	18.3	141.0	-87	423.4	76.6	453	626.6	507.2	24
23.	KONKAN & GOA	973.6	689.7	41	1429.1	1068.1	34	392.8	759.0	-48	767.3	358.5	114	3559.8	2875.3	24
24.	MADHYA MAHARASHTRA	202.4	157.0	29	298.0	240.8	24	128.0	197.1	-35	258.0	156.3	65	872.6	751.2	16
25.	MARATHWADA	180.1	138.0	30	243.7	179.1	36	172.6	186.5	-7	391.2	165.2	137	988.5	668.8	48
26.	VIDARBHA	203.6	170.6	19	293.7	307.1	-4	174.8	306.6	-43	296.9	158.8	87	968.9	943.1	3
27.	CHHATTISGARH	244.4	193.5	26	331.7	375.5	-12	221.5	364.2	-39	310.2	208.9	48	1107.7	1142.1	-3
28.	COASTAL A.P. & YANAM	82.5	105.2	-22	216.3	157.9	37	169.0	162.1	4	236.2	161.7	46	704.0	586.9	20
29.	TELANGANA	195.7	130.4	50	365.7	232.7	57	192.8	225.5	-15	290.1	163.3	78	1044.2	751.9	39
30.	RAYALASEEMA	113.6	70.9	60	183.4	92.6	98	96.5	108.5	-11	94.8	139.6	-32	488.2	411.6	19
31.	TAMIL., PUDU. & KARAIKAL	62.3	51.7	21	124.6	73.3	70	88.9	92.8	-4	117.6	118.3	-1	393.4	336.1	17
32.	COASTAL KARNATAKA	772.3	866.7	-11	1015.6	1116.3	-9	483.2	806.3	-40	508.5	305.8	66	2784.5	3095.1	-10
33.	N. I. KARNATAKA	161.0	107.1	50	194.9	123.5	58	116.8	122.0	-4	132.6	144.5	-8	607.3	497.1	22
34.	S. I. KARNATAKA	166.4	144.1	15	262.9	213.3	23	148.4	178.0	-17	115.4	146.4	-21	699.0	681.8	3
35.	KERALA& MAHE	408.4	643.0	-36	577.6	720.1	-20	416.3	426.7	-2	316.9	259.5	22	1719.1	2049.3	-16
36.	LAKSHADWEEP	160.0	330.3	-52	156.5	294.0	-47	319.5	223.2	43	154.9	165.6	-6	790.9	1013.1	-22

The following table4.3 gives the respective number of subdivisions receiving large excess, excess, normal, deficient and large deficient rainfall during the four months of monsoon season 2021.

Table -4.3: Month wise categorical distributions of no of sub divisions

Month ⇨ Category ⇩	June	July	August	September
Large Excess	3	3	0	14
Excess	13	9	4	6
Normal	12	11	14	8
Deficient	8	13	15	7
Large Deficient	0	0	3	1
No Rain	0	0	0	0

4.2.2 District wise monthly distribution of rainfall:

Monthly district wise rainfall distribution for June, July, August and September 2020 are shown in Fig.4.5 (a-d).During the season, out of 685 districts, 59 districts received large excess rainfall, 164 received excess rainfall, 290 received normal rainfall 155 received deficient rainfall and 17 received large deficient rainfall.

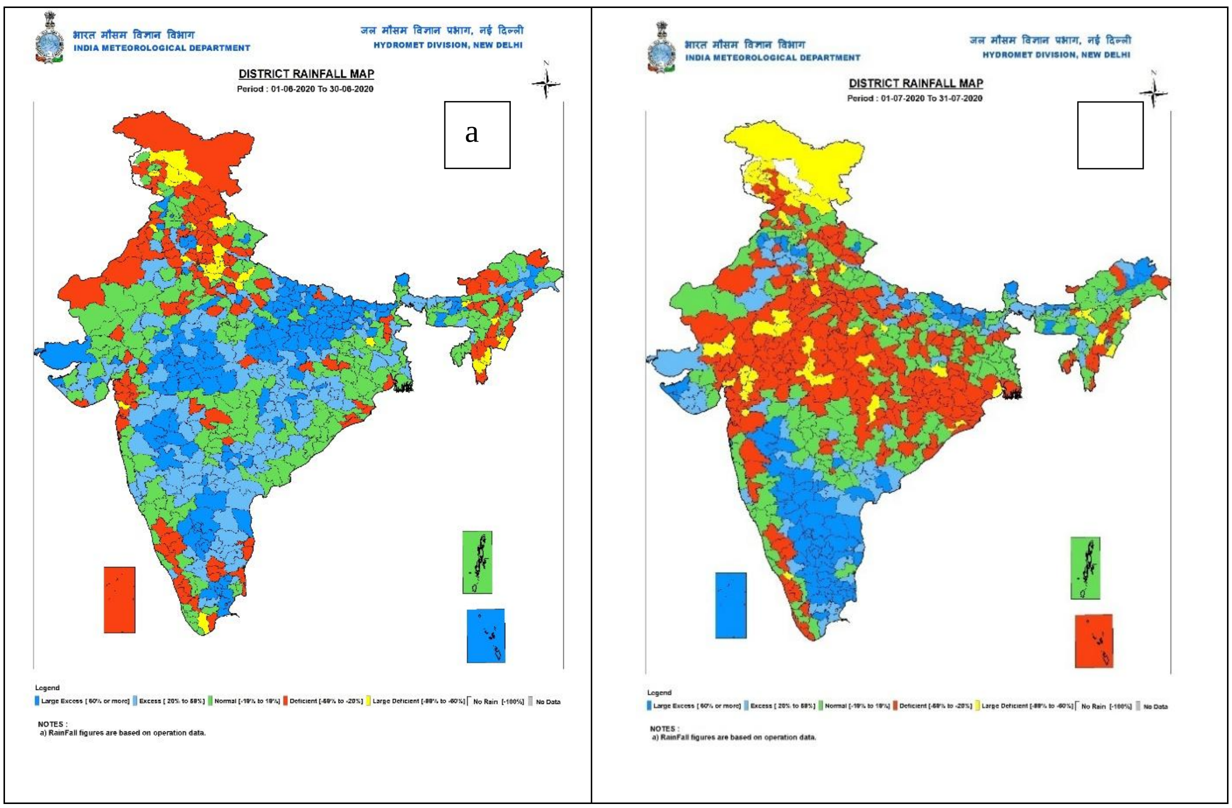
During June, most districts of A & N Islands, Assam, Meghalaya, Tripura, Sikkim, West Bengal, Odisha, Jharkhand, Bihar, Uttar Pradesh, Rajasthan, Madhya Pradesh, Goa, Maharashtra, Chhattisgarh, Andhra Pradesh, Telangana, Puducherry and Karnataka received large excess/excess/normal rainfall. Out of the total 685 districts for which data were available, 151 districts received large excess rainfall, 150 districts received excess rainfall, 203 received normal rainfall, 147 received deficient rainfall and34 districts received large deficient rainfall during June.

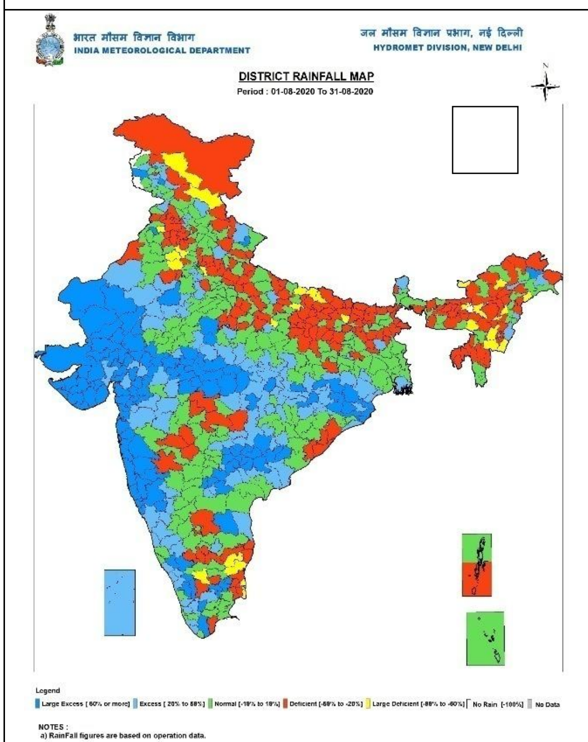
During July, most districts of Arunachal Pradesh, Meghalaya, Sikkim, West Bengal, Bihar, Chandigarh,Andhra Pradesh, Telangana,Tamil Nadu, Puducherry, Karnataka and Lakshadweep received large excess/excess/normal rainfall.Out of the total 685districts for which data were available, 87 districts received large excess rainfall, 84 districts received excess rainfall, 204 received normal rainfall, 255 received deficient rainfall, 54 districts received large deficient rainfall and one district remains in no rainfall duringin July.

During August, most districts of Sikkim, West Bengal, Odisha, Chandigarh, Delhi, Himachal Pradesh, Jammu & Kashmir, Rajasthan, M.P,Gujarat, Dadra & Nagar Haveli, Daman

& Diu, Goa, Maharashtra, Chhattisgarh, Andhra Pradesh, Telangana, Karnataka, Kerala and Lakshadweep. received Large excess/excess/normal rainfall.Out of the total 685 districts for which data were available, 127 districts received large excess rainfall, 128 districts received excess rainfall, 209 received normal rainfall, 191 received deficient rainfall, 29 districts received large deficient rainfall and one district remains in no rainfall duringAugust.

During September, most districts of A & N Island, Arunachal Pradesh, Assam,Meghalaya, Tripura, Sikkim, Bihar, Andhra Pradesh, Telangana, Tamil Nadu, Puducherry, Kerala and Lakshadweep received large excess/excess/normal rainfall.Out of the total 685 districts for which data were available, 108districts received large excess rainfall, 122 districts received excess rainfall, 139 received normal rainfall, 163 received deficient rainfall, 143 districts received large deficient rainfall and 10 remain in no rain during September.





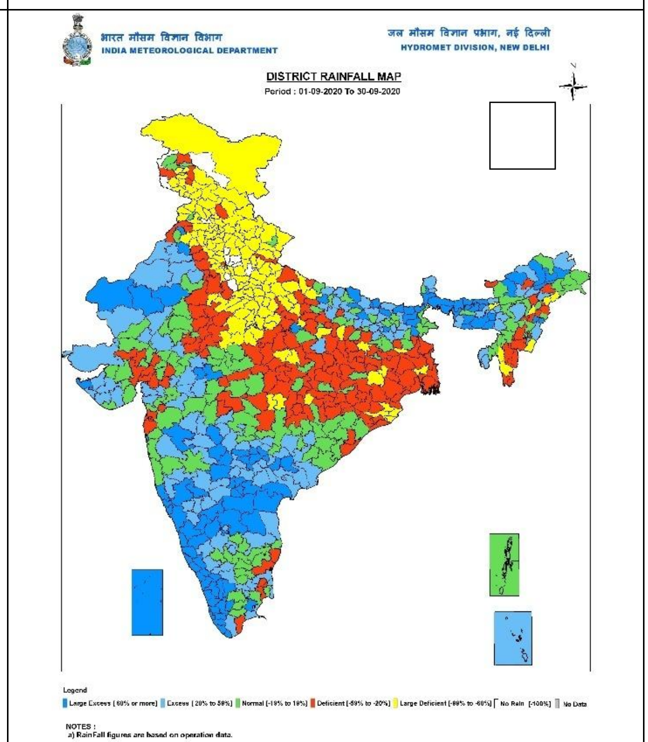


Fig.4.5(a-d) : Monthly district wise rainfall departure for June, July, August and September 2020.

The following table 4.4 gives number of districts receiving large excess (LE), excess(E), normal (N), deficient (D), large deficient(LD) or no rain (NR) during the months of June, July, August and September in each of the States.

Table 4.4: Month wise categorical distribution of no of districts in each States

STATES	JUNE							JULY							AUGUST							SEPTEMBER						
	LE	E	N	D	LD	NR	ND	LE	E	N	D	LD	NR	ND	LE	E	N	D	LD	NR	ND	LE	E	N	D	LD	NR	ND
A & N ISLAND (UT)	1	0	2	0	0	0	0	0	0	2	1	0	0	0	0	0	2	1	0	0	0	0	1	2	0	0	0	0
ARUNACHAL PRADESH	1	3	5	7	0	0	0	3	2	7	4	0	0	0	1	1	4	7	3	0	0	5	3	5	2	1	0	0
ASSAM	7	7	9	3	1	0	0	3	6	15	1	2	0	0	0	1	6	17	2	1	0	8	7	9	2	1	0	0
MEGHALAYA	2	1	4	0	0	0	0	3	1	3	0	0	0	0	0	0	3	3	1	0	0	5	2	0	0	0	0	0
NAGALAND	0	1	5	4	1	0	0	0	0	3	6	2	0	0	0	1	3	5	2	0	0	1	0	3	5	2	0	0
MANIPUR	0	1	1	4	3	0	0	1	1	2	3	2	0	0	0	2	0	4	3	0	0	0	2	2	4	1	0	0
MIZORAM	0	0	0	5	3	0	0	0	1	3	4	0	0	0	0	0	3	5	0	0	0	0	0	0	6	2	0	0
TRIPURA	0	0	4	0	0	0	0	0	0	2	2	0	0	0	0	0	0	4	0	0	0	0	2	2	0	0	0	0
SIKKIM	1	0	3	0	0	0	0	1	2	1	0	0	0	0	0	2	1	1	0	0	0	1	2	1	0	0	0	0
WEST BENGAL	0	8	10	1	0	0	0	0	3	11	4	1	0	0	0	1	14	4	0	0	0	3	0	3	12	1	0	0
ODISHA	2	10	14	4	0	0	0	0	0	7	22	1	0	0	11	9	8	2	0	0	0	0	0	8	18	4	0	0
JHARKHAND	2	2	15	4	1	0	0	0	1	10	12	1	0	0	0	5	10	9	0	0	0	1	0	6	13	4	0	0
BIHAR	27	7	3	1	0	0	0	10	7	13	8	0	0	0	0	0	8	29	1	0	0	12	14	8	3	1	0	0
UTTAR PRADESH	26	8	14	18	9	0	0	1	8	25	35	6	0	0	0	3	24	42	6	0	0	2	7	6	15	38	7	0
UTTARAKHAND	1	1	5	5	1	0	0	1	1	3	8	0	0	0	1	1	6	5	0	0	0	0	0	1	1	11	0	0
HARYANA	5	3	0	11	2	0	0	2	7	4	6	2	0	0	0	3	10	5	3	0	0	1	0	0	5	14	1	0
CHANDIGARH (UT)	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0
DELHI	0	0	1	6	2	0	0	0	3	1	3	2	0	0	0	2	6	0	1	0	0	0	0	0	1	8	0	0
PUNJAB	4	1	7	7	1	0	0	4	1	9	5	1	0	0	1	2	5	11	1	0	0	1	0	2	2	14	1	0

HIMACHAL PRADESH	**0**	**0**	**2**	**10**	**0**	**0**	**0**	**0**	**1**	**6**	**3**	**2**	**0**	**0**	**0**	**2**	**7**	**2**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**11**	**0**	**0**
JAMMU & KASHMIR (UT)	**0**	**0**	**7**	**7**	**6**	**0**	**0**	**0**	**0**	**0**	**8**	**12**	**0**	**0**	**3**	**7**	**7**	**3**	**0**	**0**	**0**	**0**	**1**	**3**	**4**	**12**	**0**	**0**
LADAKH (UT)	**0**	**0**	**0**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**1**	**0**	**0**	**0**	**0**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**1**	**0**
RAJASTHAN	**2**	**6**	**17**	**8**	**0**	**0**	**0**	**0**	**2**	**4**	**23**	**4**	**0**	**0**	**12**	**9**	**10**	**2**	**0**	**0**	**0**	**3**	**10**	**8**	**9**	**3**	**0**	**0**
MADHYA PRADESH	**30**	**14**	**5**	**2**	**0**	**0**	**0**	**0**	**1**	**7**	**38**	**5**	**0**	**0**	**20**	**14**	**16**	**1**	**0**	**0**	**0**	**2**	**6**	**14**	**19**	**10**	**0**	**0**
GUJARAT	**4**	**7**	**11**	**10**	**1**	**0**	**0**	**3**	**5**	**4**	**13**	**8**	**0**	**0**	**28**	**5**	**0**	**0**	**0**	**0**	**0**	**1**	**9**	**12**	**11**	**0**	**0**	**0**
DADRA & NAGAR HAVELI (UT)	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**
DAMAN & DIU (UT)	**0**	**0**	**1**	**0**	**1**	**0**	**0**	**1**	**0**	**0**	**1**	**0**	**0**	**0**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**1**	**0**	**0**	**0**
GOA	**0**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**2**	**0**	**0**	**0**	**0**	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**2**	**0**	**0**	**0**	**0**	**0**	**0**
MAHARASHTRA	**6**	**12**	**14**	**4**	**0**	**0**	**0**	**6**	**4**	**16**	**10**	**0**	**0**	**0**	**13**	**7**	**8**	**8**	**0**	**0**	**0**	**5**	**11**	**13**	**5**	**2**	**0**	**0**
CHHATISGARH	**5**	**17**	**4**	**1**	**0**	**0**	**0**	**0**	**1**	**8**	**17**	**1**	**0**	**0**	**4**	**14**	**9**	**0**	**0**	**0**	**0**	**0**	**3**	**6**	**17**	**1**	**0**	**0**
ANDHRA PRADESH	**3**	**4**	**6**	**0**	**0**	**0**	**0**	**7**	**3**	**2**	**1**	**0**	**0**	**0**	**1**	**3**	**6**	**3**	**0**	**0**	**0**	**5**	**5**	**2**	**1**	**0**	**0**	**0**
TELANGANA	**8**	**16**	**8**	**1**	**0**	**0**	**0**	**4**	**10**	**16**	**3**	**0**	**0**	**0**	**16**	**11**	**6**	**0**	**0**	**0**	**0**	**14**	**15**	**4**	**0**	**0**	**0**	**0**
TAMILNADU	**7**	**8**	**7**	**9**	**1**	**0**	**0**	**18**	**9**	**4**	**1**	**0**	**0**	**0**	**7**	**1**	**8**	**12**	**4**	**0**	**0**	**6**	**8**	**13**	**5**	**0**	**0**	**0**
PUDUCHERRY (UT)	**1**	**1**	**1**	**1**	**0**	**0**	**0**	**1**	**1**	**2**	**0**	**0**	**0**	**0**	**0**	**1**	**1**	**2**	**0**	**0**	**0**	**1**	**1**	**2**	**0**	**0**	**0**	**0**
KARNATAKA	**6**	**10**	**9**	**5**	**0**	**0**	**0**	**17**	**3**	**6**	**4**	**0**	**0**	**0**	**4**	**9**	**14**	**3**	**0**	**0**	**0**	**13**	**13**	**4**	**0**	**0**	**0**	**0**
KERALA	**0**	**1**	**7**	**6**	**0**	**0**	**0**	**0**	**0**	**5**	**8**	**1**	**0**	**0**	**1**	**9**	**4**	**0**	**0**	**0**	**0**	**14**	**0**	**0**	**0**	**0**	**0**	**0**
LAKSHADWEEP (UT)	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**
India	**151**	**150**	**203**	**147**	**34**	**0**	**0**	**87**	**84**	**204**	**255**	**54**	**1**	**0**	**127**	**128**	**209**	**191**	**29**	**1**	**0**	**108**	**122**	**139**	**163**	**143**	**10**	**0**

4.2.3 Daily rainfall distribution

Realtime daily rainfall (in mm) and its long term (1961-2010) normal value for the country as a whole and for the four homogeneous regions during 1 June to 30 September are shown in Fig.4.6.For the country as a whole, rainfall averaged was generally above or near normal on many days during Season. On about 20 occasions in the whole season, it was nearly more than one & half times its normal value. It was above normal at a stretch for few days viz. for the duration from 1 – 6 June, 9 – 20 June, 19 – 24 July, 28 – 31 August, 30 August – 2 September, 6 – 9 September, 11 – 17 September, 21 – 24 September and 26 – 30 September. However, it was below normal for rainfall spells during 21 June – 11 July, 15 – 18 July, 1 – 17 August, 21 – 29 August and 3 – 5 September.

Over the homogeneous region of Northwest India, daily rainfall was below normal on most of the occasions during the season. It was below normal at a stretch from 21June– 11 July, 12- 18 July, 22 – 25 July, 5 – 9 August, 11 – 20 August, 23 – 31 August and 5 – 9 September. However,rainfall was above normal at a stretch from 10 – 20 June, 28 July – 4 August, 10 – 14 September and 20 – 25September.

Over the East & Northeast India, daily rainfall was below normal on most of the days during the season. It was below normal at a stretch from 10 –14 June, 22 – 28 June, 3 – 7 July, 9 – 28 July, 2 – 6 August and most of the days during September. However, it was above normal at a stretch form 15 – 21 June, 29 July to 1 August and 25 – 29 August.

Over the Central India, daily rainfall was generally above/near normal value on many occasions during the season. It was above normal at a stretch from 1 – 5 June, 9 – 20 June, 19 – 26 July and most of the days of September. However, it was below normal at a stretch from 26 June – 11 July, 15 – 18 July, 29 July – 17 August and during most of the days August.

Over the South Peninsula, daily rainfall was below normal value on most of the days during the season. It was below normal at a stretch from 7 – 12June, 19 – 26 June, 25 July – 15 August, 9 – 12 September and 14 – 20 September. However, it was above normal at a stretch from 3 – 6 June, 13 – 18 June, 9 – 19 July, 21 – 24 July, 26 – 31 August, 2 – 8 September and 25 – 28 September.

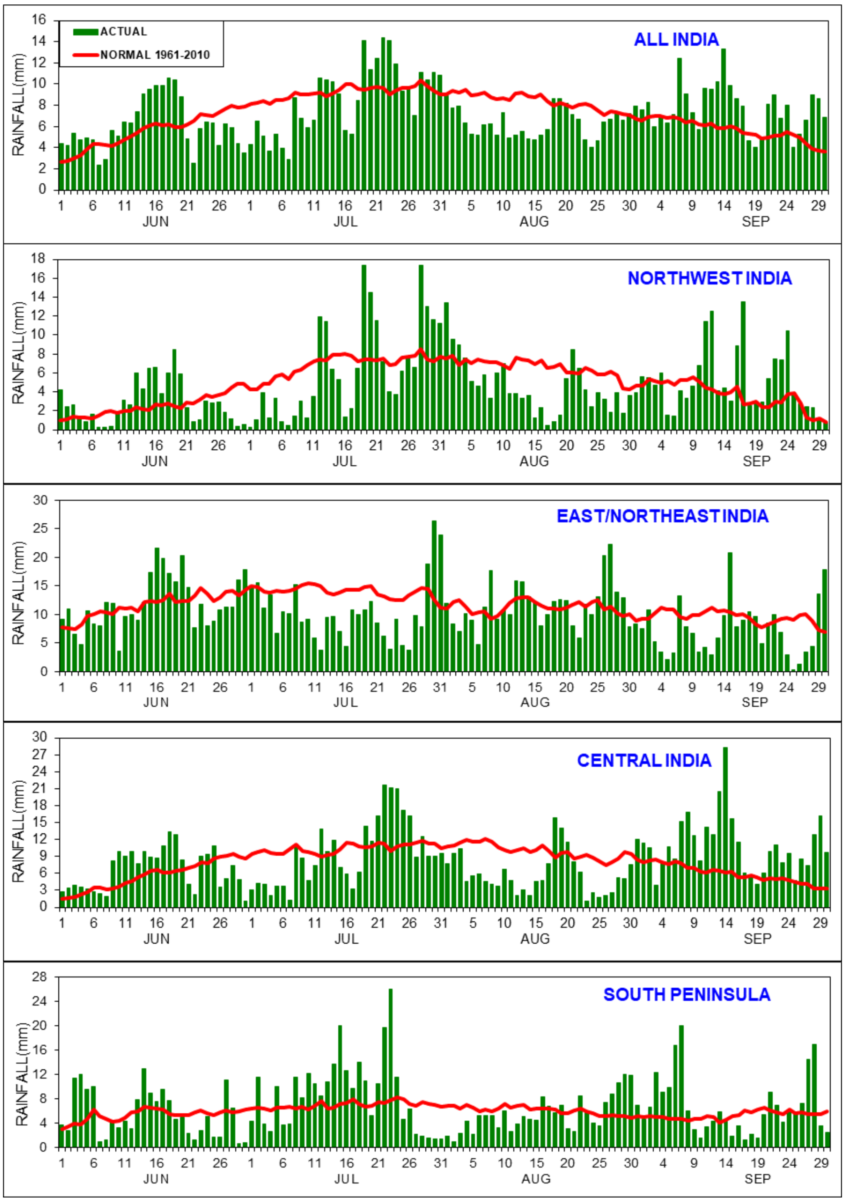


Fig.4.6 : Daily area weighted rainfall (mm) (vertical bars) and its long term (1961-2010) average (solid line) over the country as whole and the four homogeneous regions during the season.

4.2.4 Weekly rainfall distribution

Area weighted cumulative weekly rainfall percentage departure for the country as a whole and the four homogeneous regions (NW India, NE India, Central India and South Peninsula) for the period 1 June to 30 September is shown in Fig.4.7.Cumulative rainfall departure for the country as a whole was positive till the week ending 30 June. Thereafter it was negative for all the weeks of the season. ***The area weighted rainfall for the monsoon season this year was 99.3 % of its LPA value.***

Cumulative weekly rainfall departure for northwestregion was positive till week ending 30 June, thereafter it was negative for all the weeks of the season except for week ending 4 August. For East and Northeast region, the rainfall departure was positive till 30 June, thereafter it was negative for all the weeks of the season. For Central region, the rainfall departure was positive till 30 June, thereafter it was negative for all the weeks of the season, except for the week ending 28 July and 30 September. For South Peninsula region, the rainfall departure was positive for all the weeks of the season except first week.

Week by week and cumulative weekly rainfall percentage departure for each of the 36 meteorological subdivisions from 1 June to 30 September is shown in Fig.4.8 and 4.9 respectively. Weekly rainfall was large excess, excess or normal during most of the weeks (more than 50% of the weeks) for some subdivisions viz. Andaman & Nicobar island, Assam & Meghalaya, Sub-Himalayan West Bengal and Sikkim, Gangetic West Bengal, Odisha, Bihar, East and West Uttar Pradesh, Uttarakhand, Haryana, Chandigarh & Delhi, Punjab, Himachal Pradesh,

West Rajasthan, West Madhya Pradesh, Konkan & Goa, Madhya Maharashtra, Marathwada, Vidarbha, Chhattisgarh, Coastal Andhra Pradesh &Yenam, Telangana, Rayalaseema, Tamil Nadu, Puducherry & Karaikal, South Interior Karnataka, North Interior Karnataka and Kerala & Mahe.

Similarly, cumulative weekly rainfall was also large excess, excess or normal during most of the weeks (more than 50% of the weeks) for most of the subdivisions viz.Andaman&Nicobar Islands, Assam & Meghalaya, Sub-Himalayan West Bengal & Sikkim, Gangetic West Bengal, Jharkhand, Bihar, East Uttar Pradesh, Uttarakhand, Haryana, Chandigarh & Delhi, Punjab, Himachal Pradesh, West Rajasthan, East Rajasthan, West Madhya Pradesh, East Madhya Pradesh, Konkan & Goa, Madhya Maharashtra, Marathwada, Vidarbha, Chhattisgarh, Coastal Andhra Pradesh &Yenam, Telangana, Rayalaseema, Tamil Nadu, Puducherry &Karaikal, Coastal Karnataka, North Interior Karnataka and South Interior Karnataka.

4.2.5 Heavy Rainfall Events

During the 2021 southwest monsoon season, very heavy rainfall (≥ 12 cm in 24 hours)/ extremely heavy rainfall (≥ 21 cm in 24 hours) events were reported at many stations. The month wise and station wise distribution of extremely heavy rainfall events is given in Table 4.5.Record rainfall (in 24 hrs.) for the month reported during the season is given in Table 4.6.

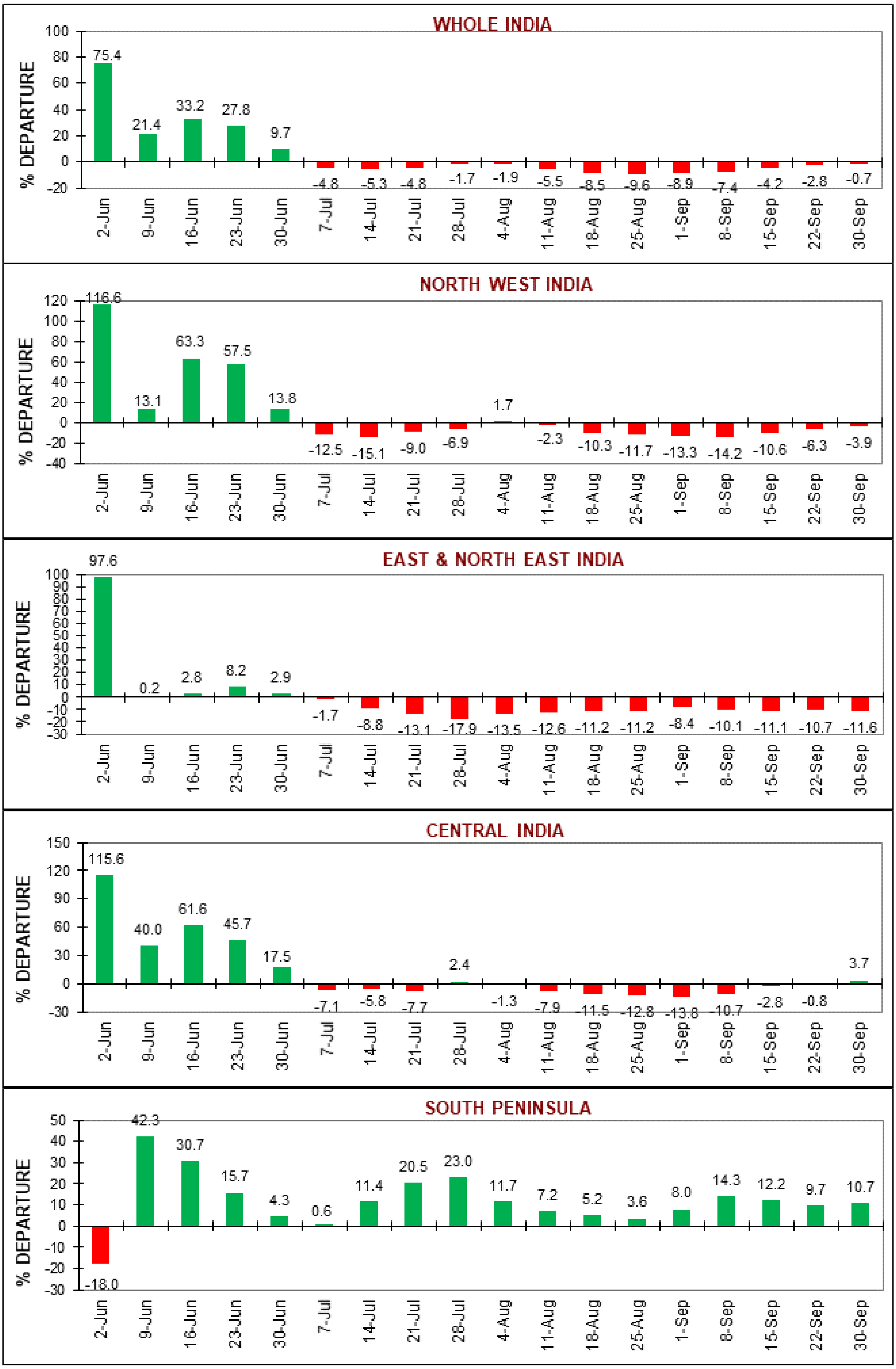


Fig.4.7: Area weighted cumulative weekly rainfall percentage departure for the country as a whole and the four homogeneous regions.

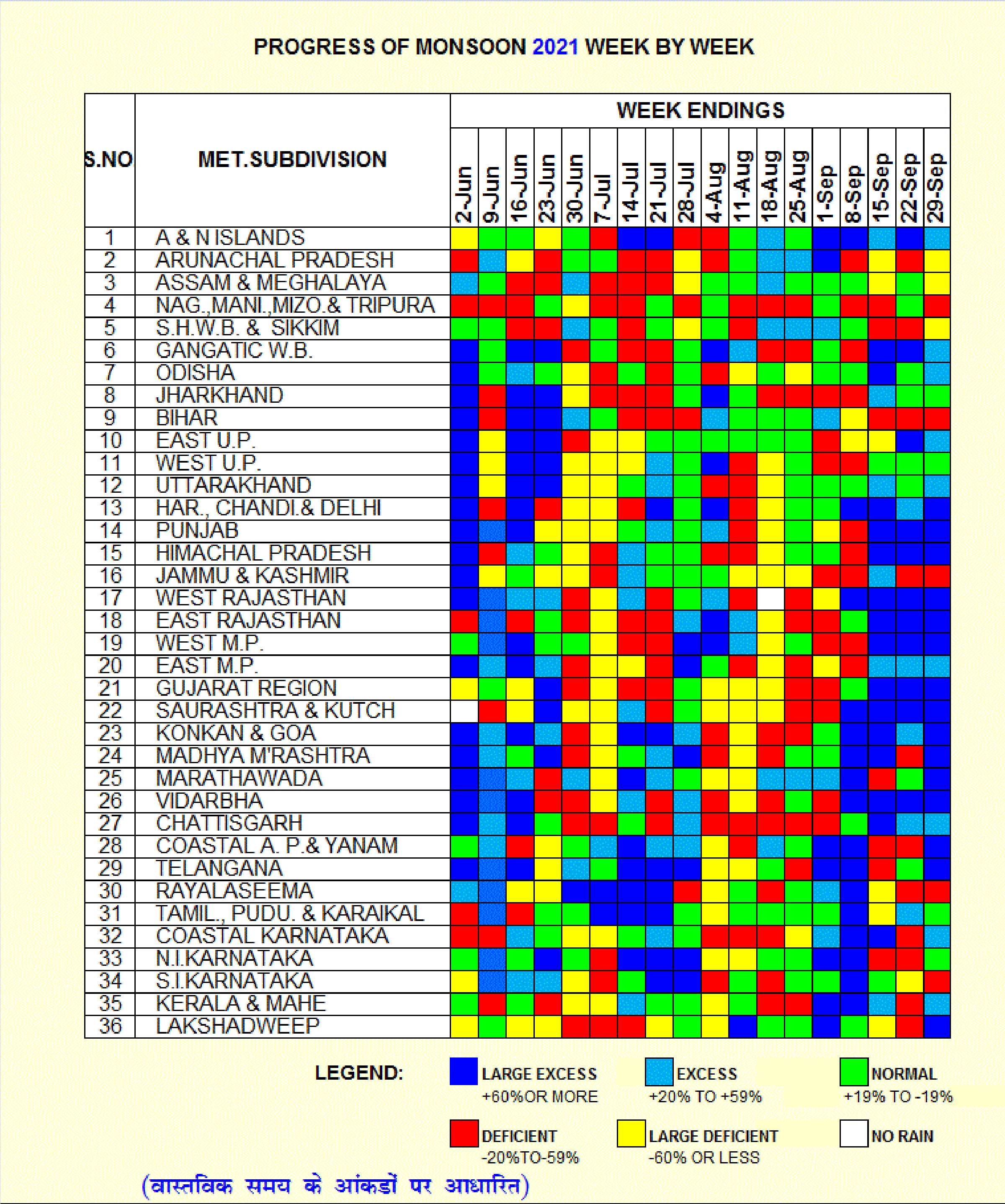


Fig.4.8: Sub-division wise weekly rainfall.

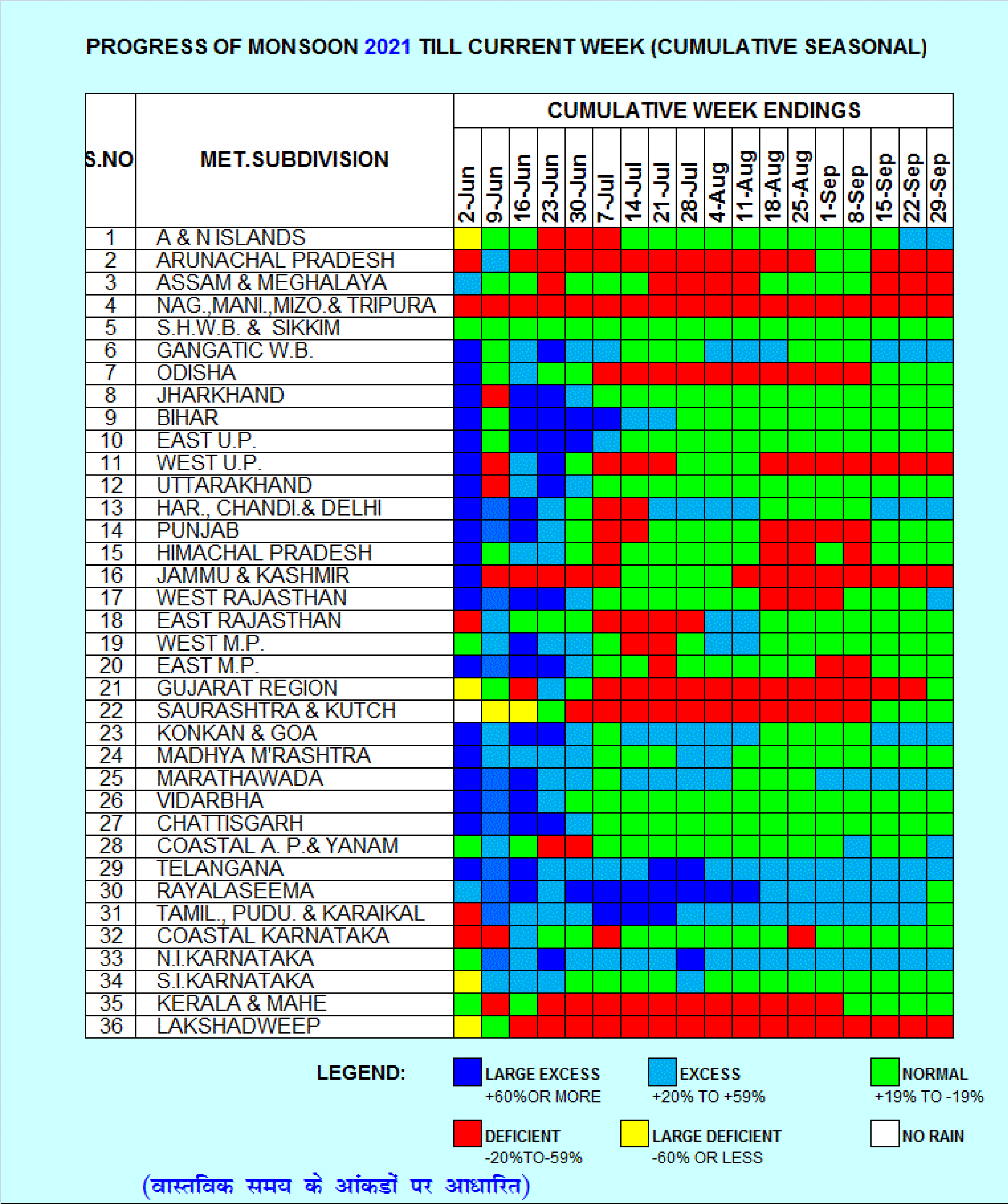


Fig.4.9: Sub-division wise cumulative weekly rainfall.

Table-4.5: Month wise list of stations, which reported extremely heavy rainfall (≥ 21 cm) in 24 hours during the monsoon season.

DATE (JUNE 21)	STATION	NAME OF SUBDIVISION	RAINFALL (cm)
4	MULKI	COASTAL KARNATAKA	39
10	SANTACRUZ - IMD OBSY	KONKAN & GOA	23
14	RATNAGIRI - IMD OBSY	KONKAN & GOA	24
15	RAMNAGAR	BIHAR	28
15	DHAURAHARA	EAST UTTAR PRADESH	27
16	BANKURA(CWC)	GANGETIC WEST BENGAL	21
16	DHAURAHARA	EAST UTTAR PRADESH	23
16	SHRIWARDHAN	KONKAN & GOA	21
17	WAKWALI_AGRI	KONKAN & GOA	21
17	GAGANBAWADA	MADHYA MAHARASHTRA	28
17	HOSANAGAR	S. I. KARNATAKA	32
18	MATHERAN	KONKAN & GOA	23
18	LINGANAMAKKI HMS	S. I. KARNATAKA	22
19	GUHAGAR	KONKAN & GOA	25
23	MARSAGHAI Arg	ORISSA	23
24	CHERRAPUNJI	ASSAM & MEGHALAYA	21
25	WILLIAMNAGAR	ASSAM & MEGHALAYA	23
28	MAWSYNRAM	ASSAM & MEGHALAYA	33
28	HALDWANI	UTTARAKHAND	21
29	CHERRAPUNJI	ASSAM & MEGHALAYA	56
30	CHERRAPUNJI(RKM)	ASSAM & MEGHALAYA	23
30	BUXADUAR	SHWB & SIKKIM	25
30	GAUNAHA	BIHAR	21

DATE (JULY 21)	STATION	NAME OF SUBDIVISION	RAINFALL (cm)
4	CHERRAPUNJI(RKM)	ASSAM & MEGHALAYA	31
12	MURUD	KONKAN & GOA	35
12	GAGANBAWADA	MADHYA MAHARASHTRA	21
13	DHARMSALA	HIMACHAL PRADESH	23
13	TALA	KONKAN & GOA	24
14	KARNAL REV	HAR CHD & DLH	25

15	HOSANAGAR	S. I. KARNATAKA	21
16	MALVAN	KONKAN & GOA	30
18	CHANDERDEEPGHAT	EAST UTTAR PRADESH	25
18	DAMAN	GUJARAT REGION	24
18	RATNAGIRI - IMD OBSY	KONKAN & GOA	25
18	KADIRI(A)	RAYALASEEMA	23
18	BHATKAL	COASTAL KARNATAKA	21
19	PALAMPUR	HIMACHAL PRADESH	23
19	UMERGAM	GUJARAT REGION	24
19	TBIA IMD PART TIME	KONKAN & GOA	29
19	OZHARKHEDA - FMO	MADHYA MAHARASHTRA	33
20	SIKANDRA RAO	WEST UTTAR PRADESH	24
20	HALDWANI	UTTARAKHAND	23
20	PATAUDI	HAR CHD & DLH	24
20	KALYAN	KONKAN & GOA	37
22	DHAURAHARA	EAST UTTAR PRADESH	37
22	SIRONJ	WEST MADHYA PRADESH	23
22	JAWHAR	KONKAN & GOA	43
22	MAHABALESHWAR-IMD OBSY	MADHYA MAHARASHTRA	48
22	BOATH	TELANGANA	21
23	BHAINSDEHI	WEST MADHYA PRADESH	27
23	POLADPUR	KONKAN & GOA	31
23	MAHABALESHWAR-IMD OBSY	MADHYA MAHARASHTRA	59
23	ASIFABAD	TELANGANA	30
23	KADRA	COASTAL KARNATAKA	34
23	LONDA	N. I. KARNATAKA	38
23	THALAGUPPA	S. I. KARNATAKA	27
24	PIRAWA	EAST RAJASTHAN	21
24	SUSNER	WEST MADHYA PRADESH	21
24	MAHABALESHWAR-IMD OBSY	MADHYA MAHARASHTRA	32
25	UDHAMPUR(IAF)	JAMMU & KASHMIR	23
25	ANUPPUR-AWS	EAST MADHYA PRADESH	23
26	MARWAR JUNCTION	WEST RAJASTHAN	21
26	JAORA	WEST MADHYA PRADESH	26
27	CHABRA	EAST RAJASTHAN	21

28	KUNDA	EAST UTTAR PRADESH	24
29	KHARAGPUR(I.I.T)	GANGETIC WEST BENGAL	26
30	ULUBERIA AWS	GANGETIC WEST BENGAL	22
31	SHAHABAD	EAST RAJASTHAN	30

DATE (AUG 21)	STATION	NAME OF SUBDIVISION	RAINFALL (cm)
1	N.LAKHIMPUR/LILABARI	ASSAM & MEGHALAYA	17
1	MAKRANA SR	WEST RAJASTHAN	24
1	HURDA SR	EAST RAJASTHAN	21
2	SHAHABAD	EAST RAJASTHAN	25
3	SHAHABAD	EAST RAJASTHAN	25
3	SHIVPURI-AWS	WEST MADHYA PRADESH	47
4	PATAN	EAST RAJASTHAN	25
10	MAWSYNRAM	ASSAM & MEGHALAYA	25
12	MAWSYNRAM	ASSAM & MEGHALAYA	27
13	MAWSYNRAM	ASSAM & MEGHALAYA	22
14	MAWSYNRAM	ASSAM & MEGHALAYA	49
14	BUXADUAR	SHWB & SIKKIM	23
14	HALDWANI	UTTARAKHAND	23
17	SALBARI	SHWB & SIKKIM	23
23	CHERRAPUNJI(RKM)	ASSAM & MEGHALAYA	33
24	MAWSYNRAM	ASSAM & MEGHALAYA	23
26	MAWSYNRAM	ASSAM & MEGHALAYA	33
31	DAMAN_ARG	GUJARAT REGION	21
31	DAHANU - IMD OBSY	KONKAN & GOA	22

DATE (SEPT 21)	STATION	NAME OF SUBDIVISION	RAINFALL (cm)
1	PATAUDI	HAR CHD & DLH	21
1	UMERGAM	GUJARAT REGION	40
1	DAHANU - IMD OBSY	KONKAN & GOA	21
2	ALIPURDUAR (CWC)	SHWB & SIKKIM	21
7	MURUD	KONKAN & GOA	47
7	NALLABELLY	TELANGANA	26
8	DEDIAPADA	GUJARAT REGION	22

8	SANGAMESHWAR DEVRUKH	KONKAN & GOA	29
9	SUTRAPADA	SAURASHTRA & KUTCH	25
13	ASTARANGA Arg	ORISSA	53
14	TALCHER	ORISSA	39
14	LODHIKA	SAURASHTRA & KUTCH	52
15	KHARAGPUR(I.I.T)	GANGETIC WEST BENGAL	28
15	AMARKANTAK	EAST MADHYA PRADESH	24
17	AZAMGARH	EAST UTTAR PRADESH	37
23	DHAURAHARA	EAST UTTAR PRADESH	21
25	KUNDA	EAST UTTAR PRADESH	21
27	VISAKHAPATNAM	COASTAL ANDHRA PRADESH & YANAM	28
28	JAKRANPALLE	TELANGANA	23
29	DURGACHACK	GANGETIC WEST BENGAL	22
29	SILVASSA	GUJARAT REGION	22
30	ASANSOL	GANGETIC WEST BENGAL	43
30	PUTKI	JHARKHAND	31
30	VISAVADAR	SAURASHTRA & KUTCH	29

Table-4.6: Record rainfall (in 24 hrs.) during the monsoon season

S. No.	STATION	RAINFALL DURING PAST 24 Hrs. (mm)	DATE	PREVIOUS RECORD (mm)	Date of record	Year of record
			(June 21)			
1	Tehri	90.2	19	55	30	1981
2	Anantpur	119.4	4	113.8	26	1926
			(July 21)			
1	Karnal	245.0	14	242	15	1968
2	Kolhapur	181.0	24	151.6	1	1953
3	Mahabaleshwar*	594.4	23	439.8	7	1977
4	Satara	172.3	24	129.2	7	1977
5	Cuddapah	125.8	5	116.8	12	1977
6	Kanyakumari	94.2	10	57	18	1968
7	Belgaum	207.8	23	192.8	10	1943
8	Belgaum (Sambra)(AP)	145.4	23	142.9	2	1984
9	Diamond Harbour	217.7	30	204.7	28	1982
			(Aug 21)			
1	DELHI RIDGE	149.2	21	127.4	2	2007
2	CAR NICOBAR(IAF)	123.2	19	73.2	16	2019
3	TINSUKIA	72	13	65.2	21	2006
4	AIZWAL	161.7	3	137.4	11	1943
5	SUKINDA	57	13	56	28	1974
6	BUNDI	202	4	155	15	2019
7	TANJAVUR	141	25	115	14	2009
8	MAHABALIPURAM	39.4	1	4.2	2	1979
9	SHIVPURI	470	3	155	25	1991
			(Sept 21)			
1	NANDYAL	126.5	1	125.8	16	2019
2	VISAKHAPATNAM AP	267	27	161.2	20	2005
3	PENDRA ROAD	183.2	15	173	15	1987
4	CANACONA	185	5	135.4	14	2015
5	HANSI	130	4	22	16	2011

6	NANCOWARY	162.2	28	121.4	6	1964
7	ANGUL	201.6	14	148.8	6	1939
8	BHUBANESWAR AERO	199.9	13	137	9	2005
9	PHULBANI	181.6	14	154.4	12	1968
10	PURI	342.5	13	210.8	20	1934
11	TONDI	107.5	18	78.5	23	1985
12	MAHABALIPURAM	56	6	42.4	20	1979
13	AZAMGARH	370	17	225	14	1976
14	FURSATGANJ	186.3	16	137.8	27	2019
15	DAMAN	327.8	1	267.8	4	2012
16	BANKURA	354.3	30	208	1	1978

Conclusions:

The Southwest Monsoon season rainfall over the country as a whole during 2021 was 99.3% of Long Period Average (LPA). Rainfall distribution was generally fairly well distributed over major parts of the country.*The season observed significant intra seasonal variations in rainfall as realized rainfall in September (135.1 % of LPA) being above normal, June (109.6 % of LPA) & July (93.2 % of LPA) being normal and August (76 % of LPA) being below normal.*

The homogeneous region of South Peninsula (110.7% of LPA) received above normal rainfall, Northwest India (96.1% of LPA) and Central India (103.7% of LPA) received normal rainfall, while East & Northeast India (88.4% of LPA)received below normal rainfall.

During the season, out of 36 meteorological subdivisions, ten subdivisions received excess and 20 received normal rainfall. Six subdivisions received deficient rainfall.Out of 6 deficient sub-divisions, 3 were from east & northeast India (Arunachal Pradesh, Assam & Meghalaya, Nagaland, Manipur, Mizoram & Tripura), 2 were from northwest India(West Uttar Pradesh and Jammu & Kashmir and Ladakh) and 1 was island from south peninsula (Lakshadweep).

During the season, out of 685 districts, 59 districts received large excess rainfall, 164 districts received excess rainfall, 290districts received normal rainfall, 155districts received deficient rainfall and 17 received large deficient rainfall.

For the country as a whole, rainfall averaged was generally above or near normal on many days during Season. On about 20 occasions in the whole season, it was nearly more than one & half times its normal value. It was above normal at a stretch for few days viz. for the duration from 1 – 6 June, 9 – 20 June, 19 – 24 July, 28 – 31 August, 30 August – 2 September, 6 – 9 September, 11 – 17 September, 21 – 24 September and 26 – 30 September. However, it was below normal for rainfall spells during 21 June – 11 July, 15 – 18 July, 1 – 17 August, 21 – 29 August and 3 – 5 September.

5

Part-A

Assessment of GFS model Forecasts during South West Monsoon, 2021

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5.1 Introduction

India Meteorological Department (IMD) routinely provides forecasts in medium range scale using deterministic model Global forecast system (GFS). GFS model is providing forecast at T1534L64 resolution for 10 days at 00 and 12 UTC and issuing forecast for 5 days at 06 and 18 UTC. GFS model initially implemented at IMD in 2010 with T382L64 resolution (Durai et al., 2011). Model is subsequently upgraded to T574L64 in 2012 and upgraded to T1534L64 (~12 km) in 2016. In 2018 model upgraded from spectral based sigma framework to NOAA Environmental Modelling system (NEMS) framework with a modular structure for all NCEP models and associated changes in land surface, cumulus parameterization schemes and introduction of Near-Surface Sea Temperature (NSST) (White et al., 2018). GFS model uses initial conditions created from GDAS operational at National Centre for Medium range Forecasting (NCMRWF) in providing forecasts (Prasad et al., 2021). GFS data assimilation system at NCMRWF employs hybrid 4D Ensemble Variational (EnsVar) assimilation system with 80 member EnKF ensembles. The system utilizes satellite observations and conventional observations from all major operational meteorological centres and it consist of large number of observations over India region. Observation pre-processing system at NCMRWF receives observations through different channels like EUMETCAST, GTS, DBNET and from NOAA (National Oceanographic and Atmospheric Administration), CMA (China Meteorological Administration) and KMA (Korea Meteorological Administration) through their respective data access servers and processed in near real time. GFS model version 14.1.0 operational at IMD uses two-time level semi-implicit semi-Lagrangian dynamics in Gaussian grids with 3072×1536 grid points horizontally and 64 hybrid sigma pressure levels in vertical direction. Model employs near surface sea temperature (NSST) model for providing lower thermal boundary conditions during the integration of model forecasts. Model employs following schemes Zhao – Carr microphysics, Scale and Aerosol aware (SAS) deep and shallow convection, modified rapid radiative transfer model (RRTMG) radiation, eddy diffusivity mass-flux (EDMF) based strongly unstable planetary boundary layer (PBL), eddy-diffusivity counter-gradient based weakly unstable planetary boundary layer (PBL) and NOAH land surface model for parameterizing various physical processes occurring in the sub-grid scales (Johny and Prasad, 2020)

Onset of the southwest monsoon over Kerala had taken place over Kerala on 3rdJune and advanced to many parts of northern and central India by 13thJune and further advanced to more parts of North Arabian Sea, Gujarat, Uttar Pradesh, Rajasthan by 19thJune and there was no further advance of the system till 11thJuly. South west monsoon covered entire country by 13thJuly by advancing further to Delhi and remaining parts. In June mean rainfall over India was 110% of long period average. In June extreme rainfall events observed mostly over Konkan-Goa region and Karnataka and some extreme events are reported in Assam, Bihar, Orissa, East Uttar Pradesh and Uttarakhand. In July rainfall over the country was 93% of its long period average (LPA). In July South peninsula received 126 % of LPA and all other regions it was below normal. In July also a number of extreme rain events occurred in Konkan-Goa region and Karnataka. There were occurrences of some extreme events in other part of country also. In August rainfall over the country was 76 % of LPA. In East and North East India rainfall was 103 % of LPA in August and it was below normal in other regions. In this month a number of extreme rainfall events occurred in East Rajasthan and West M.P region and Assam Meghalaya region. Delhi Received heavy rainfall of the amount on 21stAugust. In September month cyclone Gulab caused heavy rainfall over coastal Andhra Pradesh, Telangana, Maharashtra and Gujarat. Depression systems also caused good amount of rainfall Odisha and Gujarat in September. In September, rainfall over the country was 135 % of LPA and rainfall was above normal in all regions except in the region East and North East India. Central India received rainfall above 88 % than normal. In this study model performance in the months from June to September is investigated

5.2 Configuration of GFS model

GFS model is operationally running in Mihir High Performance Computing System at NCMRWF. The models use time step of450 seconds in dynamics computations and a time step of 225 seconds in physics computations. Models produce forecasts in NEMS format binary files in Gaussian grids and converted to grib2 format by employing post processing techniques. GFS model takes 60 minutes with 50 nodes for 10 day forecasts.

5.3 Rainfall Verification

Rainfall forecasts over Indian region is evaluated with respect to 0.25° gridded rainfall combining IMD rain gauge observations and satellite derived rainfall (Mitra et al., 2009). Figure 5.1 shows cumulative rainfall for the month of June in observations and GFS model forecasts of lead times from day1 to day5. In this month major rainfall activity is seen over West Coast of India, Central India, North East region, Himalayan foothills region, Bihar and Bengal. In west coast cumulative rainfall in the range 100-150 cm is observed along Maharashtra coast. Cumulative rainfall in the range 30-50 cm is observed in the central parts of India. It can be seen that in day1 forecasts GFS rainfall over central India is mostly missing while better represented in forecasts of longer lead times. Rainfall over East U.P., Bihar and Bengal is not represented in model forecasts which are more evident in shorter lead times. Figure 5.2 shows mean difference between observation and GFS model forecasts (observation – model). Positive mean difference indicates regions where model under estimates and vice versa. It can be seen that model under estimates rainfall forecast in most of the region except in North East India and sea region of west coast. Figure 5.3 show root mean square error (RMSE) of GFS forecasts with respect to observations. It can be seen that RMS error shows same pattern in forecasts of all lead times while RMSE values are less over central India in 24hour forecasts. RMS error of 80-100 cm can be seen over Northern Bay of Bengal (BOB) in day1 to day5 forecasts. Cumulative rainfall observations for the month of July and corresponding GFS model forecasts are shown in Figure 5.4. It can be seen that in July month main rainfall activity is occurred over west coast, central India, Foot hills of Himalayas, east and north east part of India. In west coast especially over coastal regions of Maharashtra and Goa very good amount of rainfall (even greater than 250 cm in some pockets) is observed. It can be seen that in day1 forecast rainfall over Himalayan foothill region, central and East India is not properly represented in IMD GFS forecast. Mean difference between observation and model forecast for GFS model is shown in Figure 5.5. In North East regions model overestimated rainfall as seen in the month of June. In west coast model forecast show under estimation in the model. RMSE plot is shown in Figure 5.6 and RMSE values are high over west coast and North and east Bay of Bengal in both the models. Cumulative rainfall observed in the August month and corresponding GFS model forecasts are shown in Figure 5.7. Major rainfall activity in August is seen over west coast, West Madhya Pradesh, East Rajasthan, East Uttar Pradesh, Bihar, Bengal and North East states. In west coast rainfall in the range of 50-100cm is reported in August. In GFS model forecasts rainfall over West Madhya Pradesh and East Rajasthan is over estimated to a large spatial extent except in day1 forecast. Mean difference between observations and GFS forecasts plots and RMSE is given in Figure 5.8 and 5.9 respectively. GFS overestimated rainfall over the North East region and sea region of west coast. The rainfall over land region of west coast and west Madhya Pradesh, East Rajasthan is under estimated. High RMS errors are seen over East Central BOB, West Madhya Pradesh and East Rajasthan region, Himalayan Foothills and over Bangladesh. RMS errors over the west coast are relatively less compared to June and July. Along the border of Assam and Bangladesh cumulative rainfall amounts exceeding 200 cm is reported, which is not represented in model forecast.

Cumulative rainfall observed in the September and corresponding GFS model forecasts are shown in Figure 5.10. Major rainfall activity in this month is reported over west coast especially over Gujarat and Konkan and Goa, Madhya Maharashtra, Marathwada, Chhattisgarh, Odisha, West Bengal, some parts of coastal Andhra-Pradesh, Telangana, East Uttar Pradesh, North East states, Punjab, Himachal Pradesh and Uttarakhand. It can be seen that model is able to predict the general characteristics of rainfall activity for the month. There is some over estimation of rainfall over central part of India, under estimation of rainfall over BOB in day1 forecast. Figure 5.11 shows the mean difference in observation and GFS model forecast for the month of September and RMSE plot is given in Figure 5.12. In forecasts over estimation can be seen over west Madhya Pradesh, East Rajasthan, some parts of Gujarat. As seen in the case of other months, rainfall is under estimated over land part of west coast, BOB, some parts of Saurashtra, Odisha and Bengal. High RMS errors are seen over Gujarat region, BOB, West Bengal and Odisha in the model.

Different categorical skill scores are computed over Indian domain for different rainfall thresholds. Rainfall thresholds are defined on the basis of IMD's classification of rainfall in different rainfall categories like light, moderate, heavy etc. Figure 5.13 shows Critical Success Index (CSI) computed over entire Indian domain. It can be seen that CSI score is > 0.2 for the rainfall amount less than 35.6mmwhich can be seen in the forecastwith lead time of 7days. For higher rainfall thresholds skill score is less than 0.2. Gilbert Skill score (GSS) computed over the Indian domain is shown in Figure5.14. It can be seen that GSS skill score is >0.1 for the rainfall threshold up to 35.6mm. False Alarm ratio (FAR) over the Indian domain is shown in Figure5.15. It can be seen that FAR is < 0.5 for rainfall threshold up to 2.5 mm.

5.4 Summary

Model is able to represent general characteristics of rain fall in all the months. There is an overall under estimation of rainfall over land region of west coast of India and over estimation of rainfall over North East region in both the models. In June and July GFS is not able to represent rainfall over central India region in day1 forecasts which has come better at forecast of longer lead times. In August GFS over estimated rainfall over West Madhya Pradesh and East Rajasthan region. Various skill scores show model has a reasonable skill in the forecast of light to moderate rainfalls

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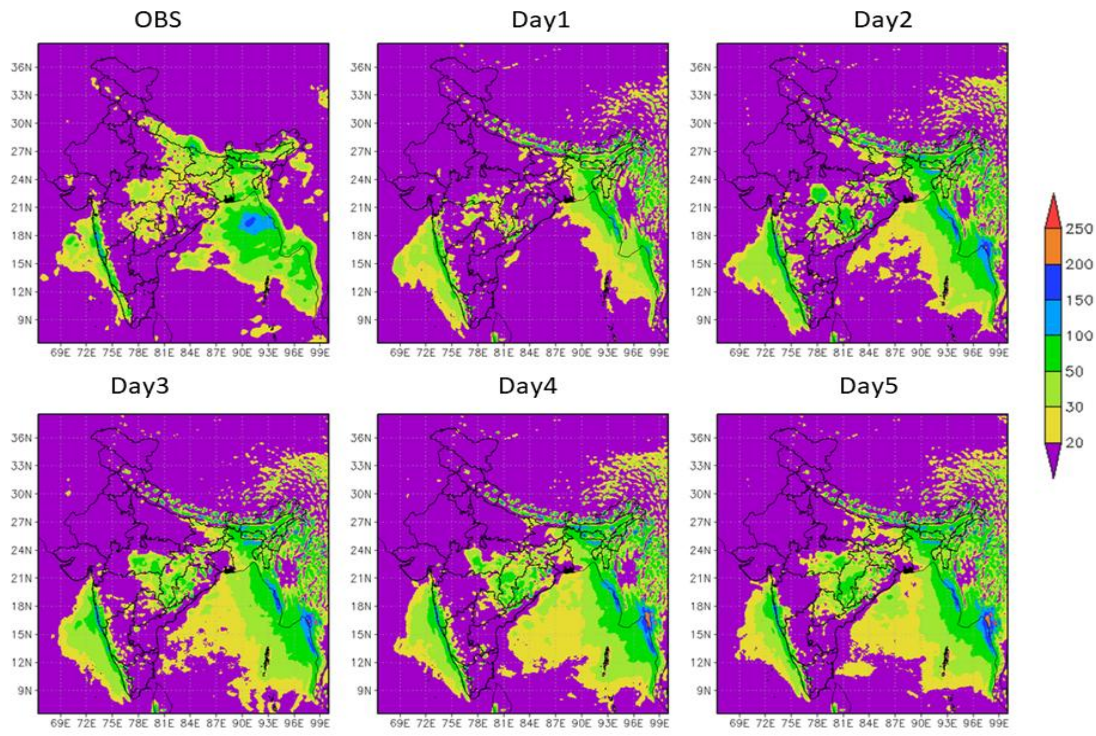

Figure 5.1 Cumulative rainfall observed and GFS forecast for the month of June

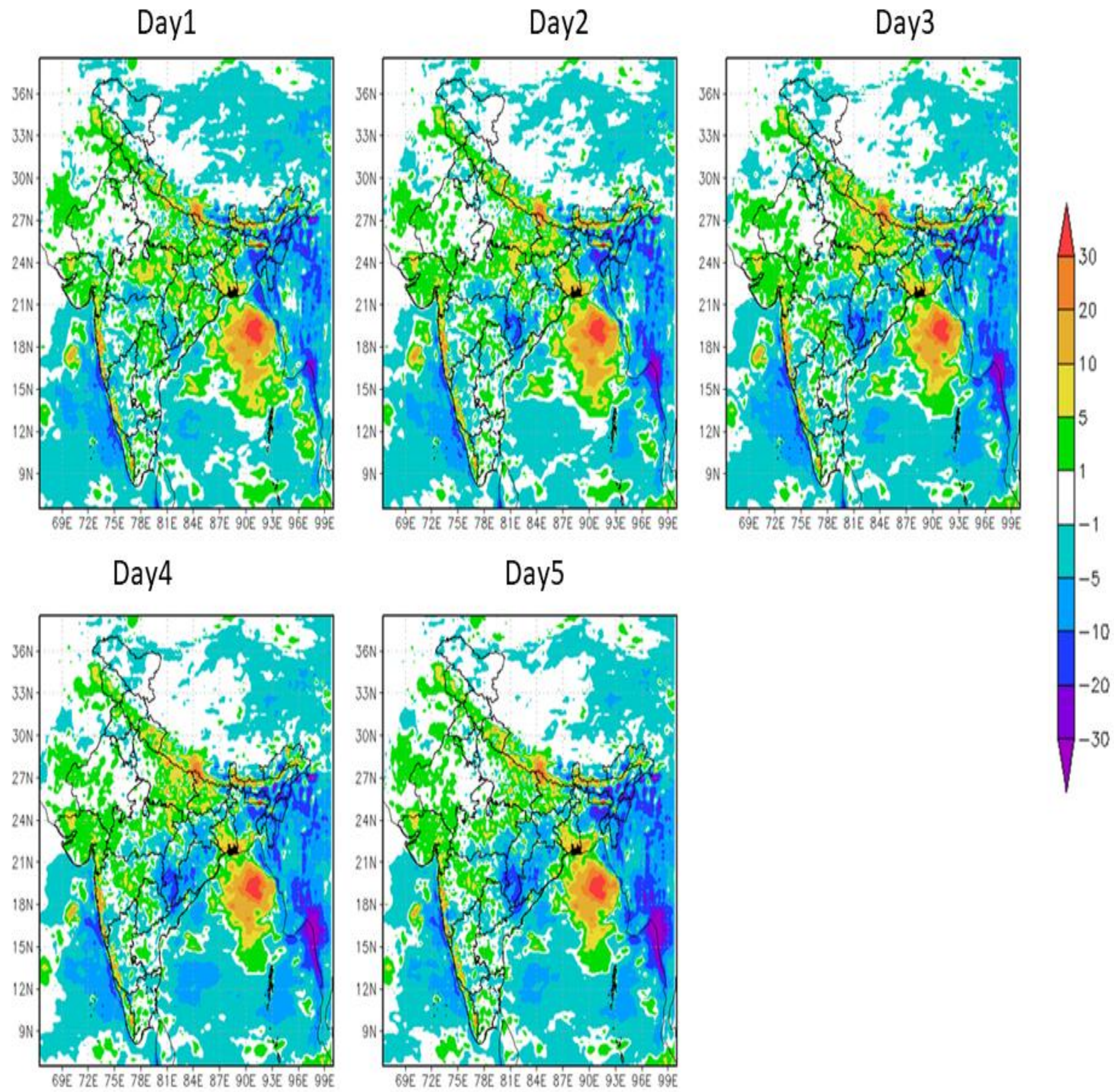

Figure5.2 Mean difference between observed rainfall and GFS forecast (observed-model) for the month of June

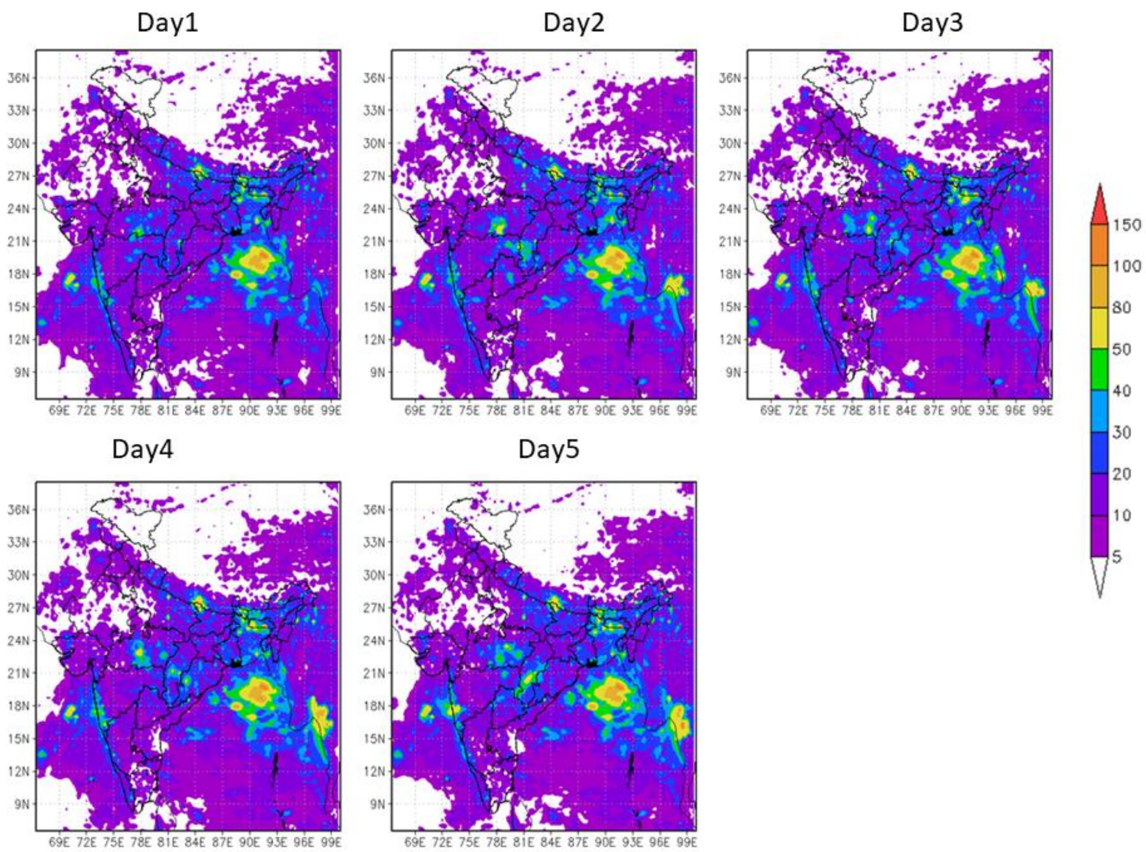

Figure 5.3 RMS error in GFS forecasts with respect to observed rainfall for the month of June

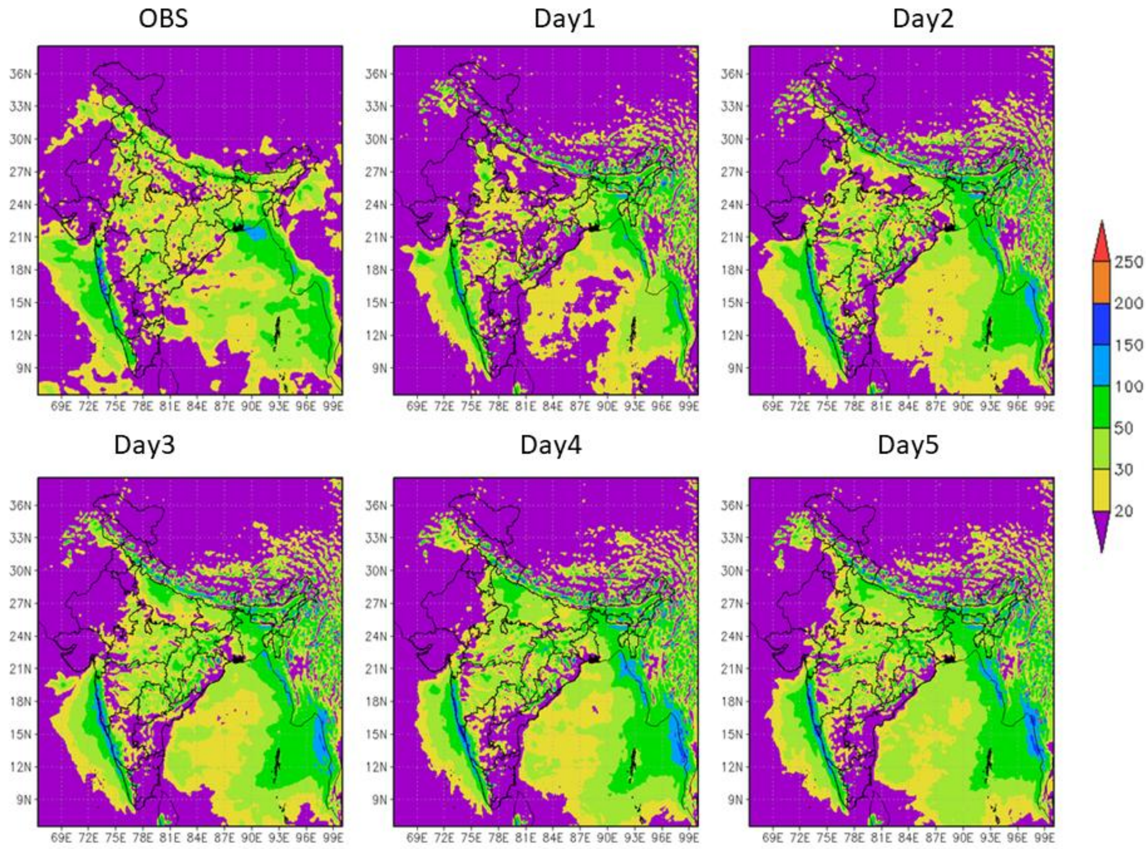

Figure 5.4 Cumulative rainfall observed and GFS forecast for the month of July

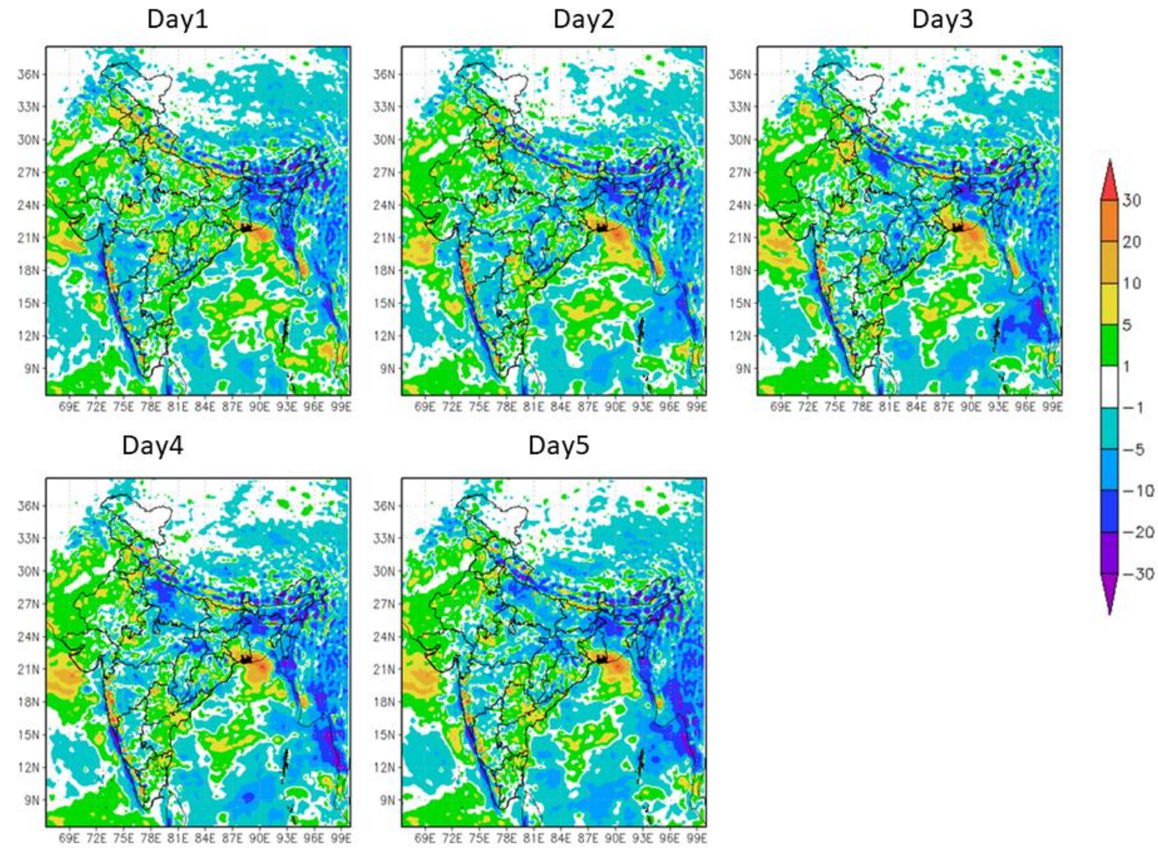

Figure 5.5 Mean difference between observed rainfall and GFS forecast (observed-model) for the month of July

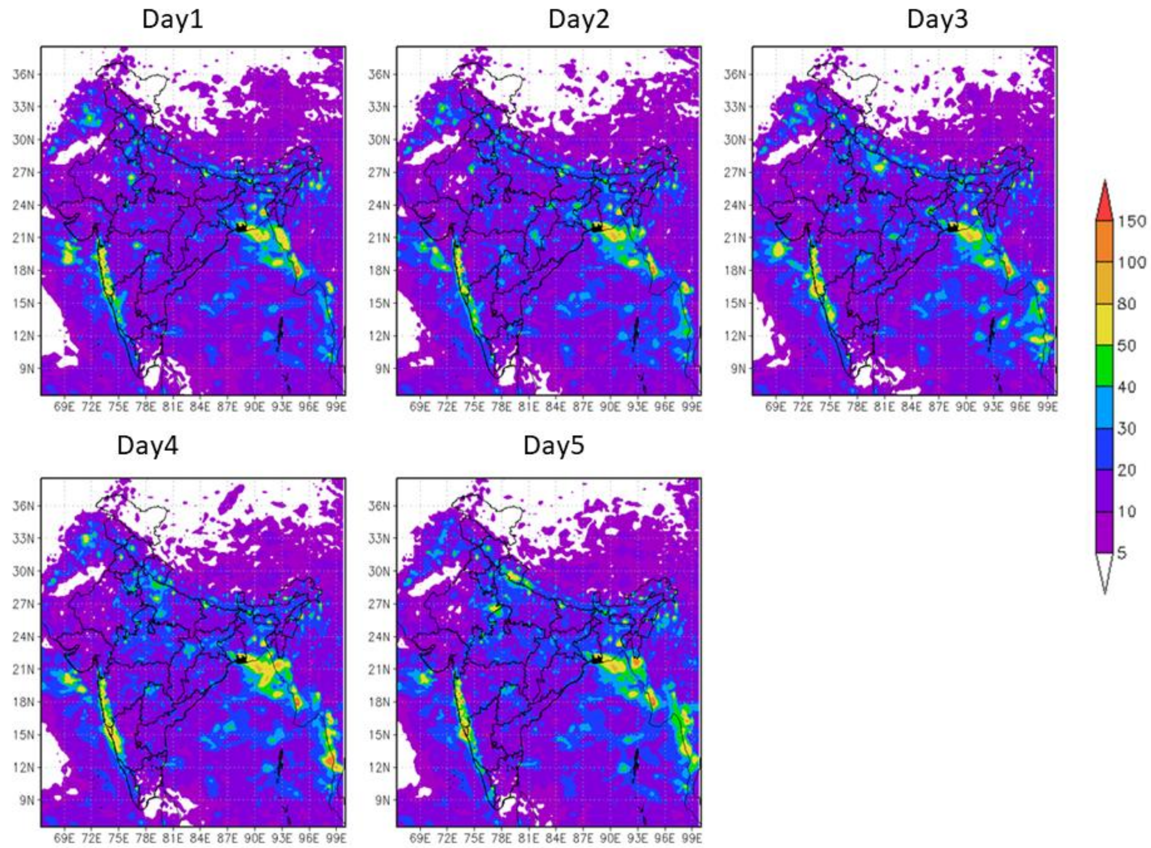

Figure 5. 6 RMS error in GFS forecasts with respect to observed rainfall for the month of July

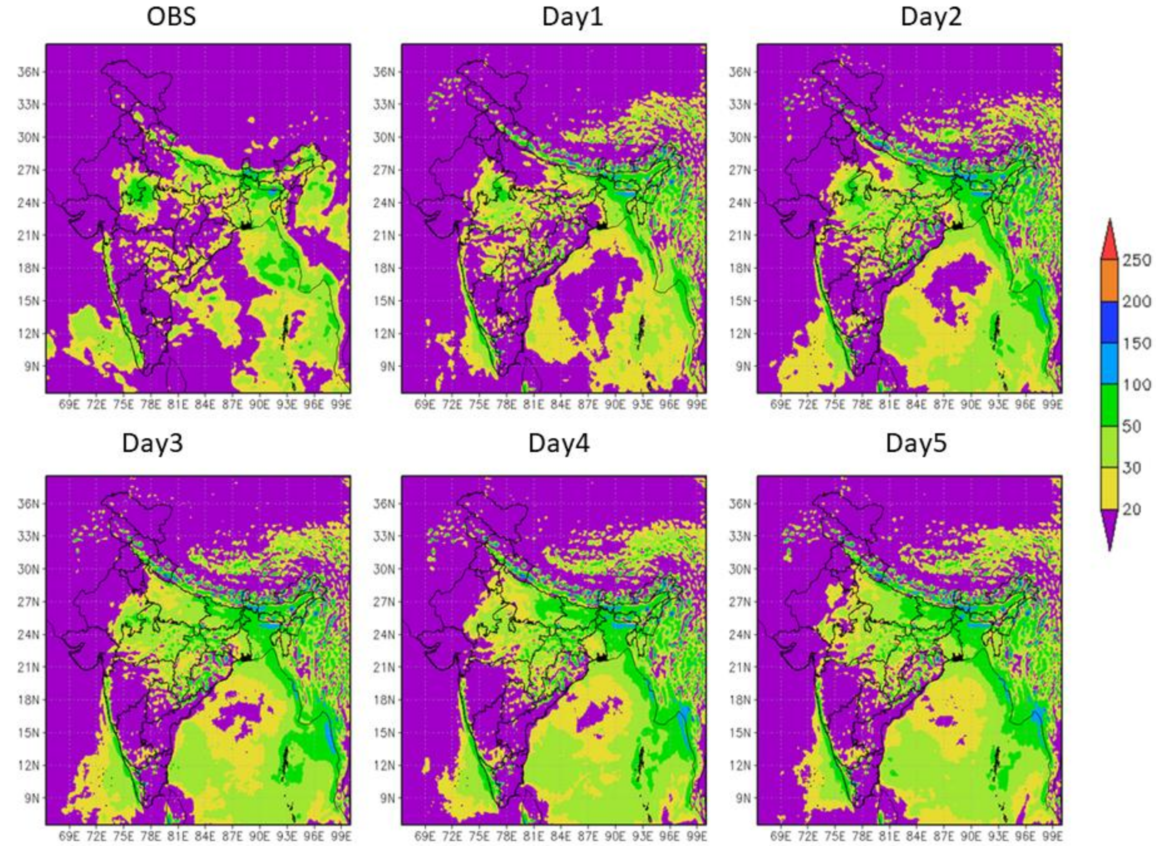

Figure 5.7 Cumulative rainfall observed and GFS forecast for the month of August

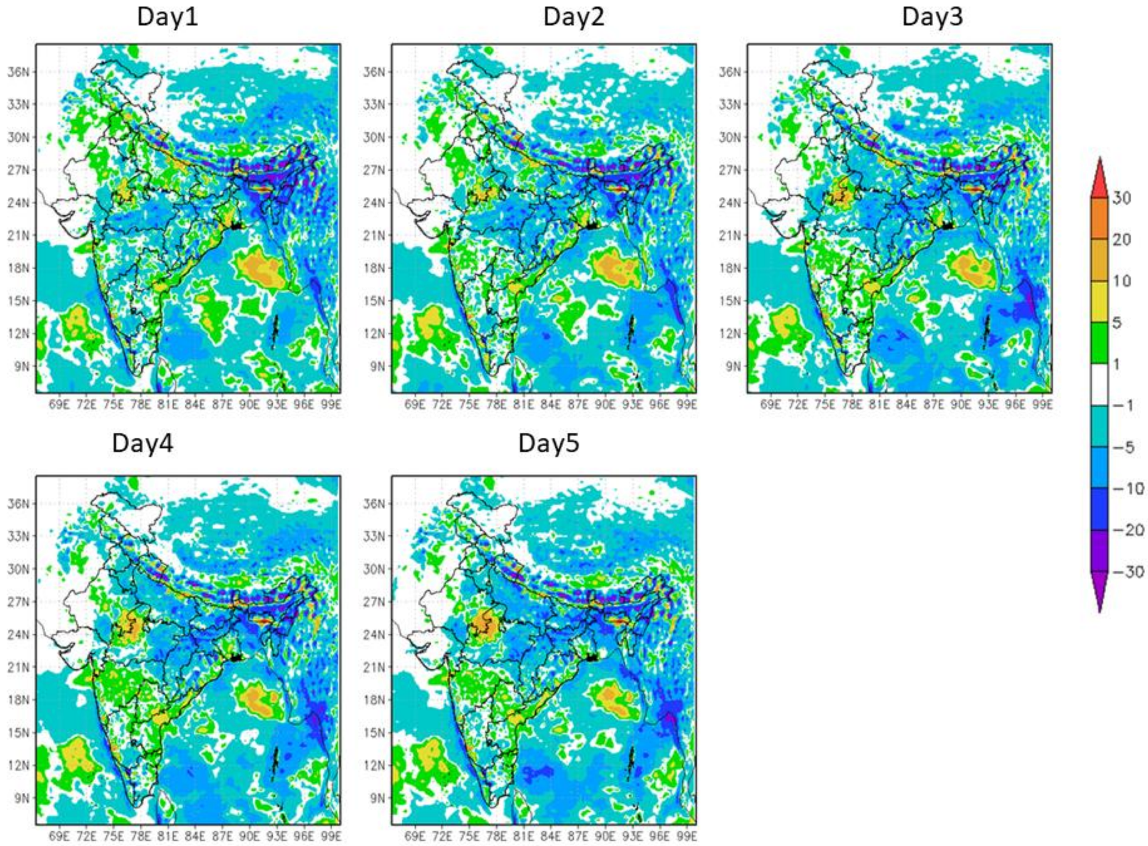

Figure 5.8Mean difference between observed rainfall and GFS forecast (observed-model) for the month of August.

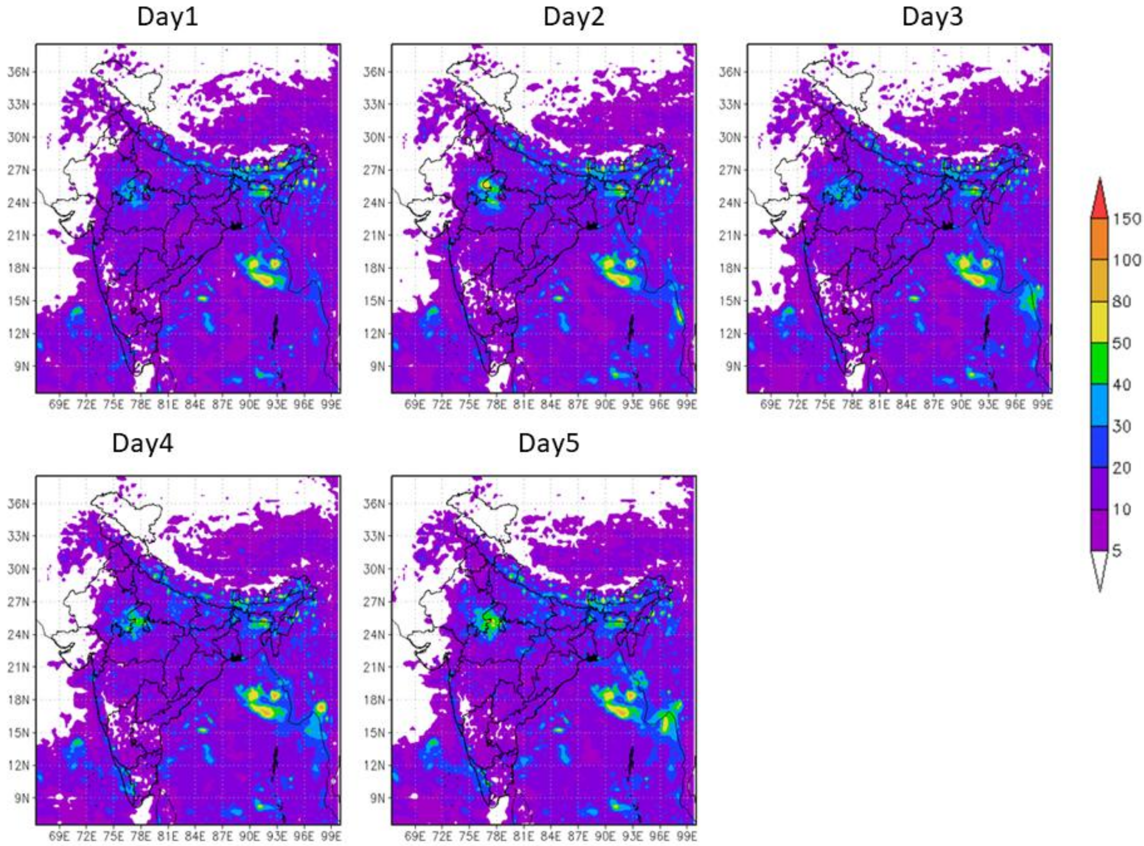

Figure 5.9 RMS error in GFS forecasts with respect to observed rainfall for the month of August.

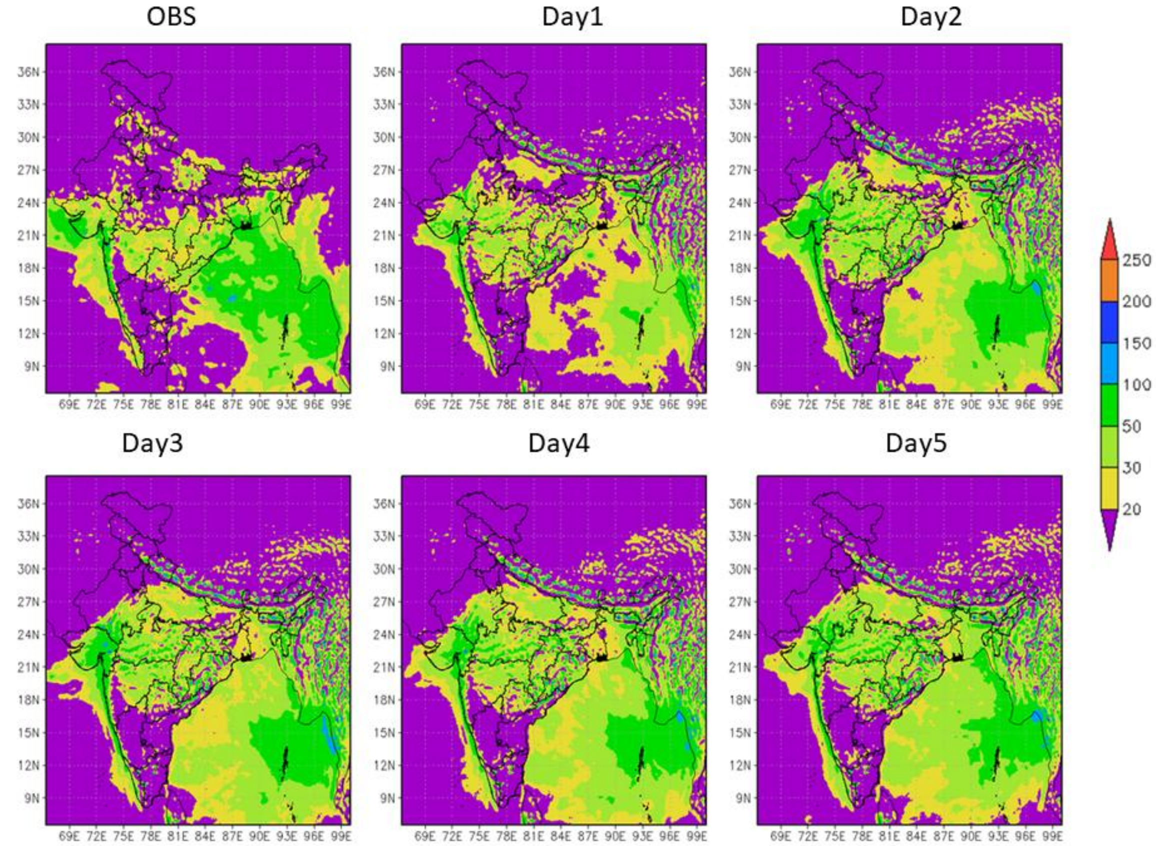

Figure 5.10 Cumulative rainfall observed and GFS forecast for the month of September.

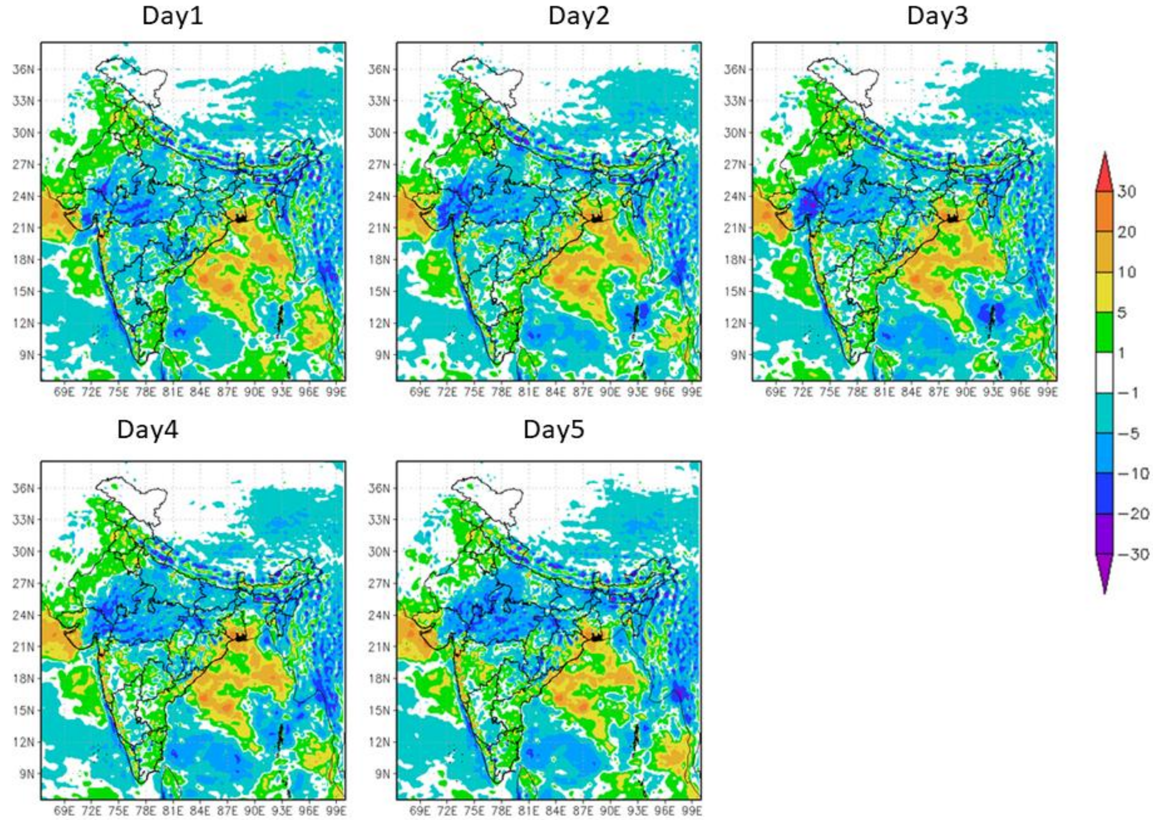

Figure 5.11 Mean difference between observed rainfall and GFS forecast (observed-model) for the month of September.

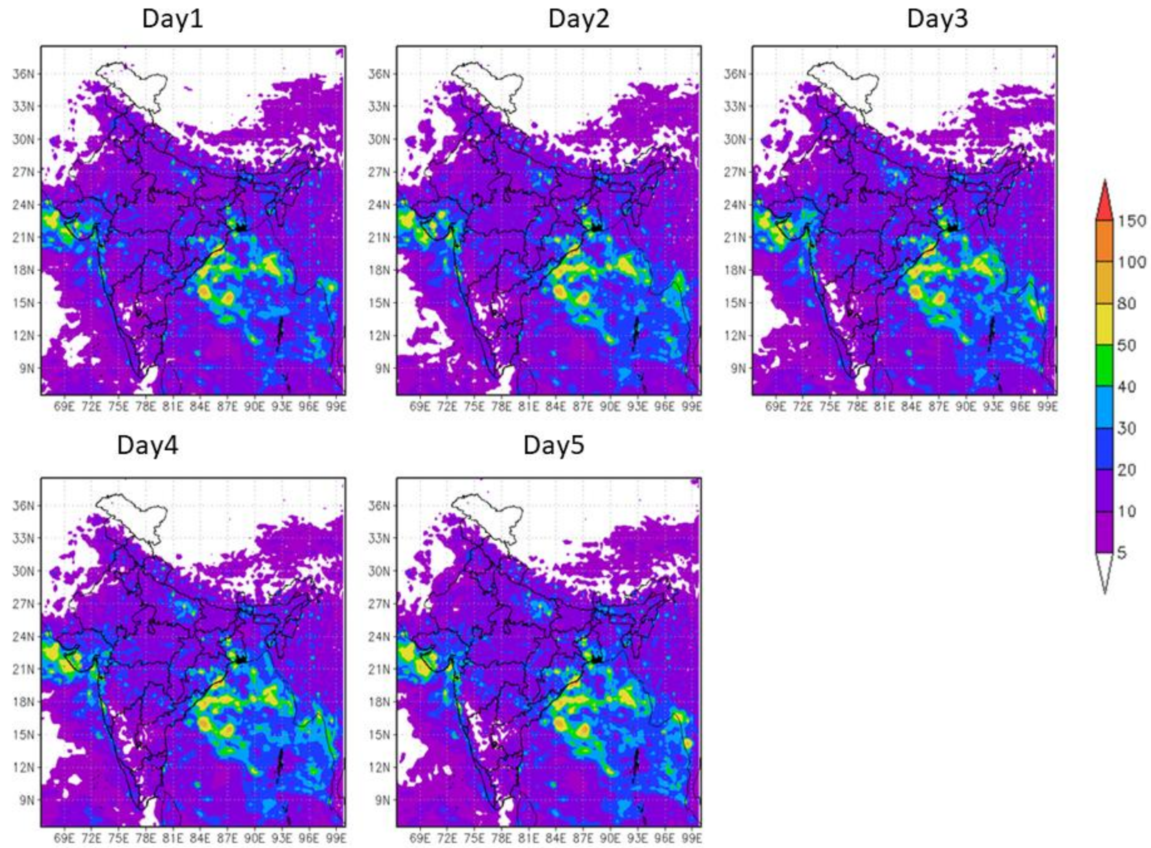

Figure 5.12 RMS error in GFS forecasts with respect to observed rainfall for the month of September

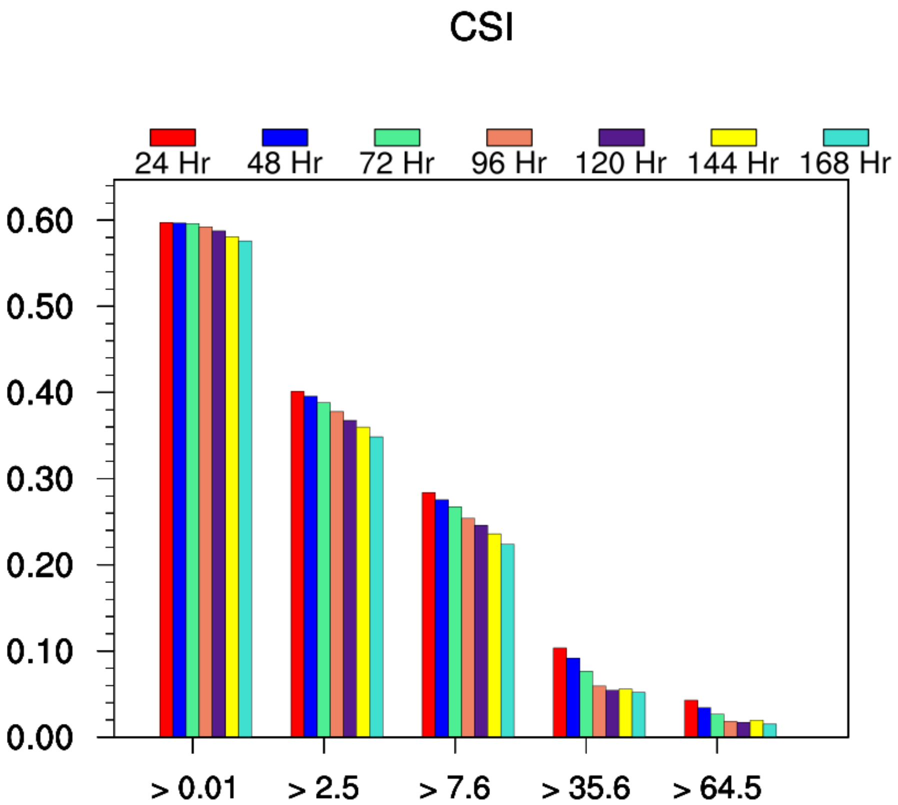

Figure 5.13 Critical Success Index (CSI) over entire Indian domain for different rainfall thresholds

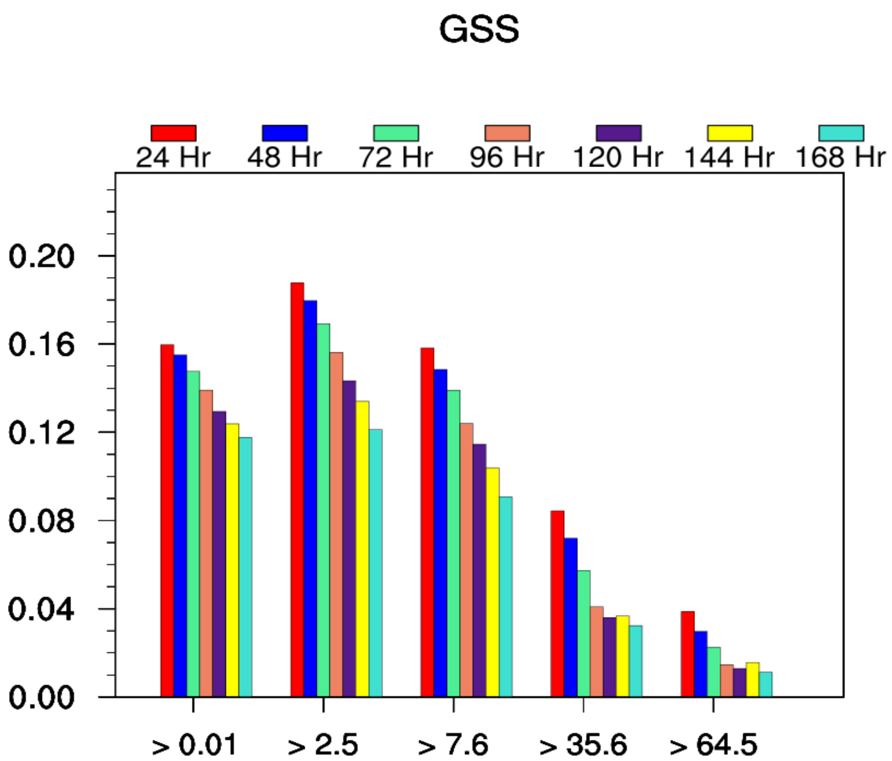

Figure 5.14 Gilbert Skill Score (GSS) of rainfall forecast over Indian domain for different rainfall thresholds

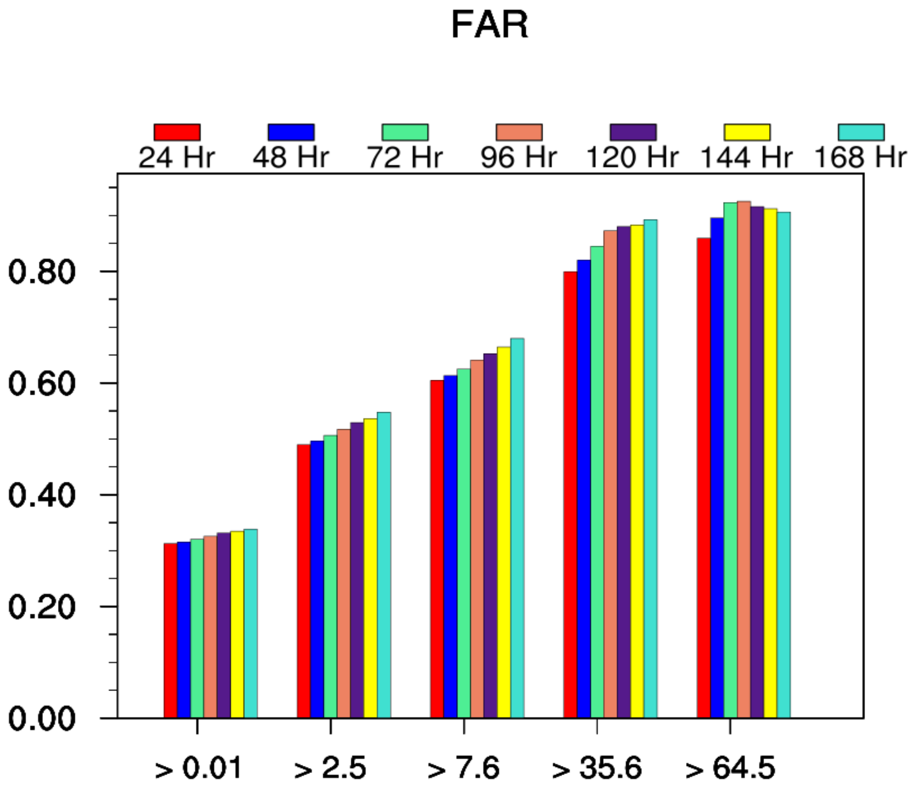

Figure 5.15False Alarm Ratio (FAR) of rainfall forecast over Indian Domain for different rainfall thresholds

PART-B

Assessment IMD WRF model forecast during South West Monsoon 2021

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5.5 Introduction

India Meteorological Department (IMD) routinely provides forecasts in short range scale using Weather Research and Forecast (IMD-WRF) model. The systemuses Regional Grid-point statistical interpolation (Regional-GSI) as the assimilation system and assimilate large number of conventional and satellite observations over Indian region. Model is run at 3 km resolution with the forecast integration time of 72 hours at 00 and 12 UTC and with forecast integration time of 48 hours at 06 and 18 UTC. Model employs Advanced Research WRF (ARW) as dynamical core and uses following schemes Noah Land surface model, Rapid radiative transfer model (RRTM) long wave radiation, Goddard shortwave short wave radiation, Mellor-Yamada-Janjic (MYJ) Planetary Boundary Layer (PBL), Grell 3D Ensemble cumulus convection for parameterizing various physical processes occurring in the sub-grid scales. Performance of IMD-WRF model during south west monsoon period June to September, 2021 is evaluated in this study.

5.6 Model configuration

Model is operationally running in Mihir High Performance computing system at NCMRWF. IMD-WRF produces forecasts in NETCDF format and conversion to grib2 format is carried out for specific applications. Model takes ~ 90 minutes with 151 nodes for forecast of 72 hours. Model employs 1951 × 1851 grids in horizontal direction with the center at 22.5 °N and 81.2 °E and 45 levels in vertical direction with the model top at 50 hPa. IMD-GFS model outputs are used for providing initial and boundary conditions for the model.

5.7 Rainfall Verification

Rainfall forecasts over Indian region is evaluated with respect to 0.25° gridded rainfall combining IMD rain gauge observations and satellite derived rainfall (Mitra et al., 2009). Figure 5.16 shows mean rainfall for the month of June in observations and WRF model forecasts of lead times from day1 to day3. Figure 5.17 and Figure 5.18 shows mean error and RMSE in rainfall respectively for the month of June. In this month major rainfall activity is seen over west coast of India, central India, north east region, Himalayan foothills region, Bihar and Bengal. In west coast cumulative rainfall in the range 100- 150 cm is observed along Maharashtra coast. Cumulative rainfall in the range 30-50 cm is observed in the central parts of India. Model is able to represent general characteristics of rainfall over all regions. There is an over estimation of rainfall over North East region and in west coast. In day2 and day3 forecasts model overestimated rainfall over East M.P, Chhattisgarh, Jharkhand, East U.P. and Odisha. There is some under estimation of rainfall in Himalayan foot hills especially over the Nepal region. In day1 forecasts RMSE values are less in comparison to forecasts of longer lead times.

It can be seen that in July month main rainfall activity is occurred over west coast, central India, Foot hills of Himalayas, East and North East part of India. In west coast especially over coastal regions of Maharashtra and Goa very good amount of rainfall (even greater than 250 cm in some pockets) is observed. Figure 5.19 shows mean rainfall for the month of July in observations and WRF model forecasts of lead times from day1 to day3. Figure 5.20 and Figure 5.21 shows mean error and RMSE in rainfall respectively for the month of July. Model is able to represent general features of rainfall for the month which shows close match with observations in their day1 forecast. It can be seen that model over estimated rainfall over North East region and in west coast and at the same time interior side of west coast model shows underestimation. In day2 and day3 forecasts rainfall in some parts over the U.P. and Bihar is over estimated in the model. In day1 forecasts RMSE values are less in comparison to forecasts of longer lead times.

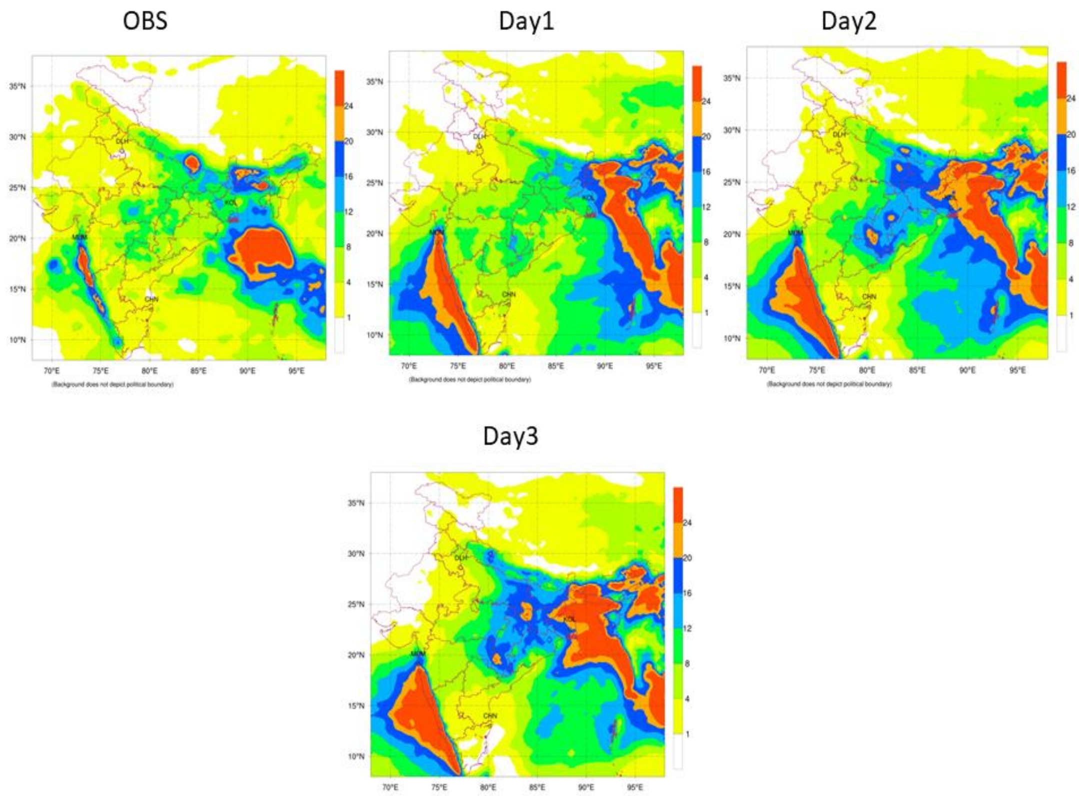

Figure 5.66 Mean rainfall for the month of June.

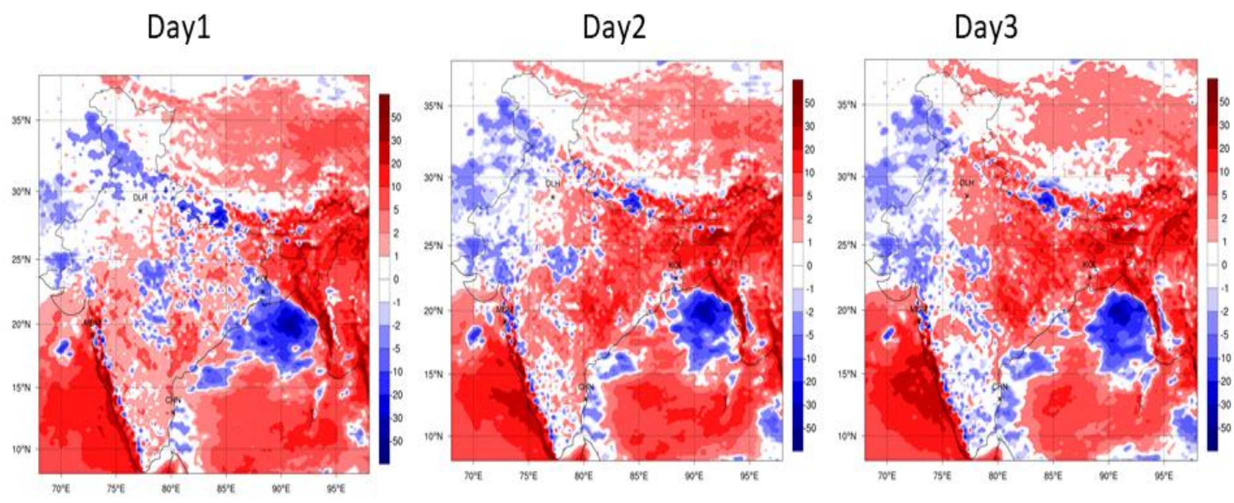

Figure 5.17 Mean Error in the rainfall for the month of June.

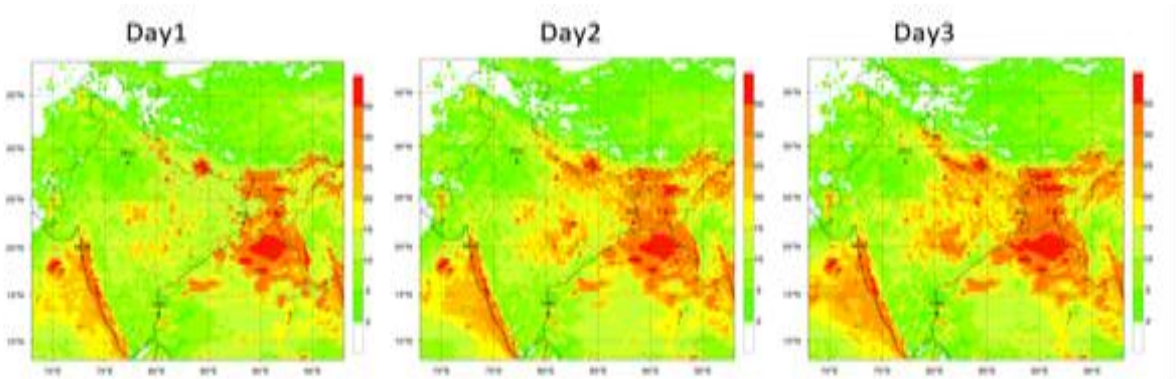

Figure 18 RMSE in rainfall for the month of June

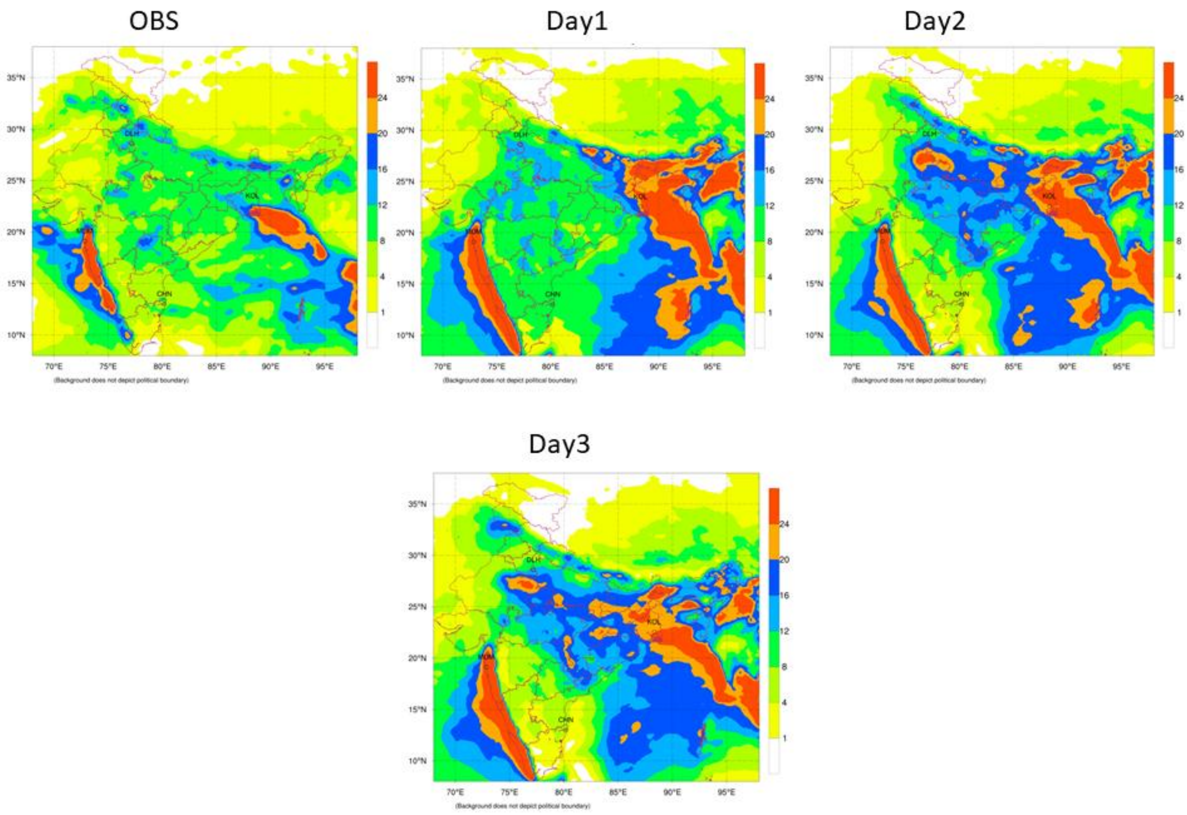

Figure 5.19 Mean rainfall for the month of July.

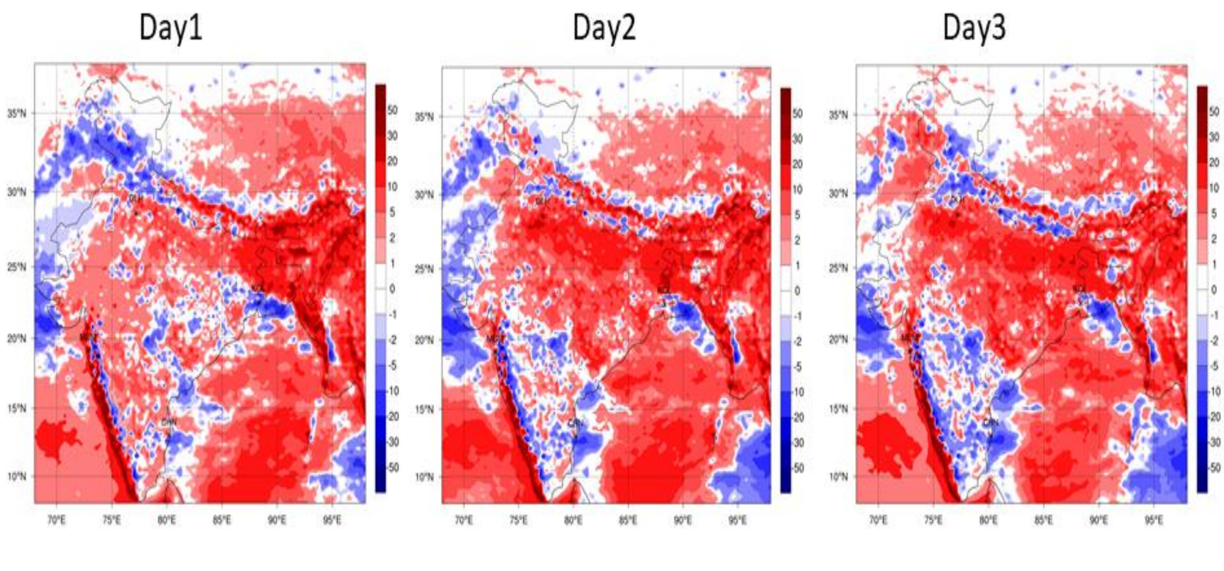

Figure 5.20 Mean error in rainfall for the month of July.

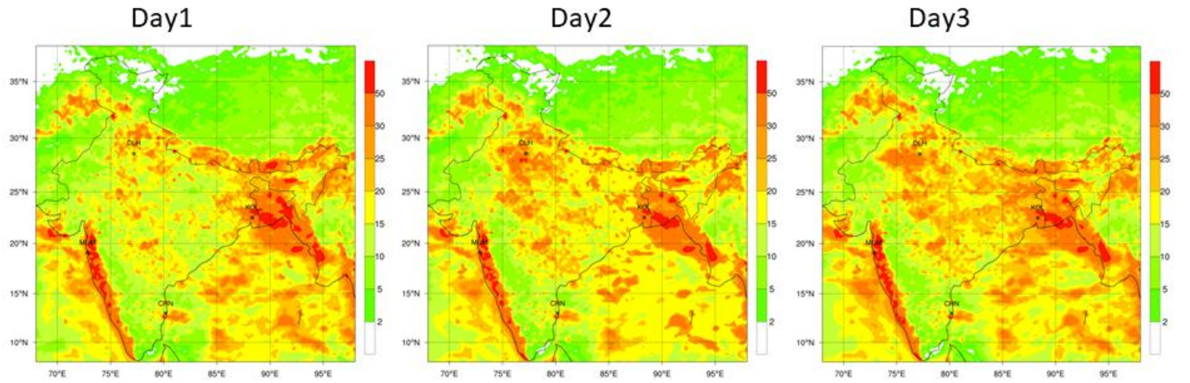

Figure 5.21 RMSE in rainfall for the month of July

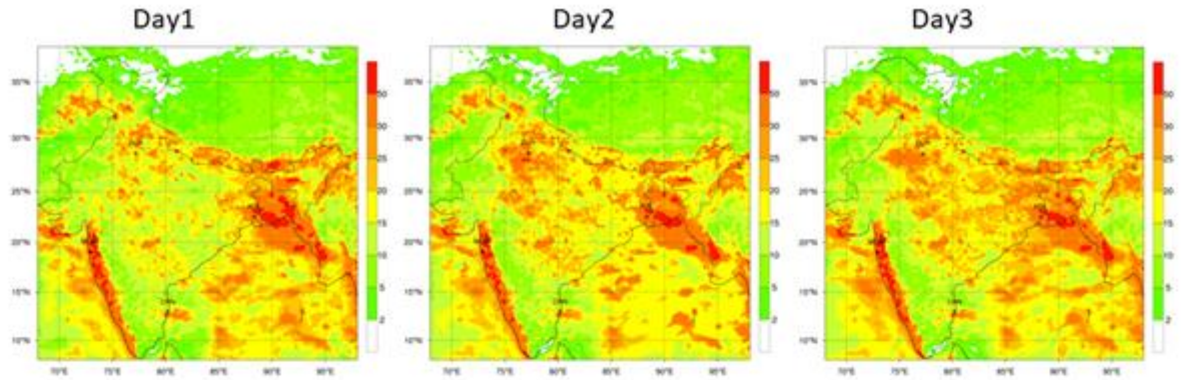

Figure 21 RMSE in rainfall for the month of July

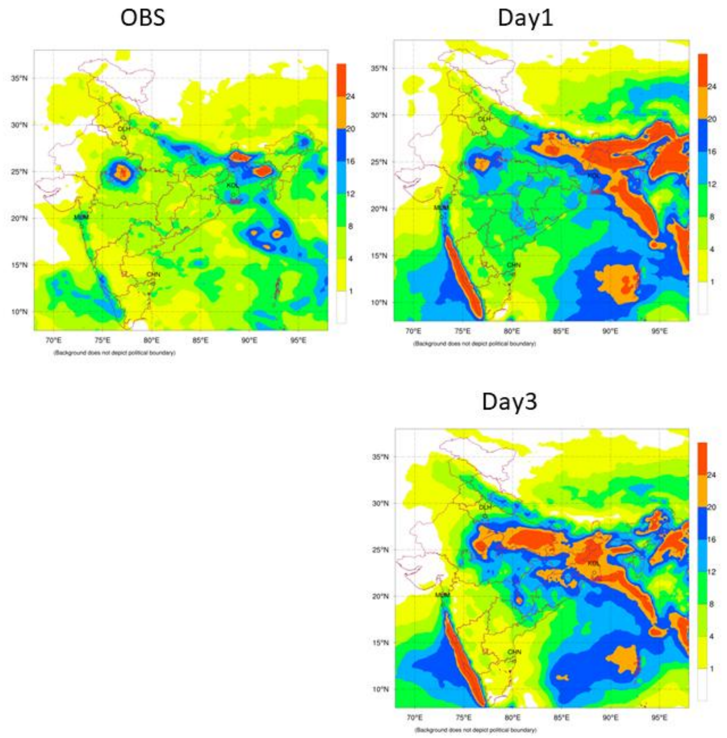

Figure 5.22 Mean rainfall for the month of August.

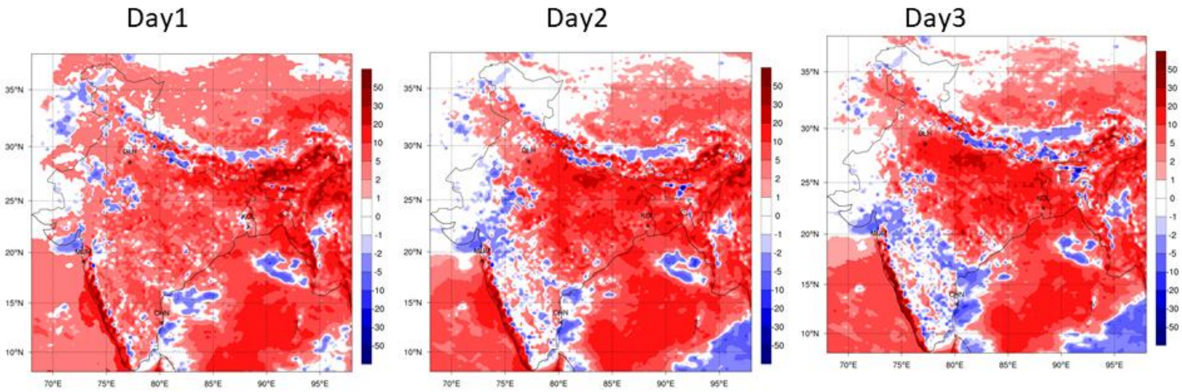

Figure 5.23 Mean error in rainfall for the month of August

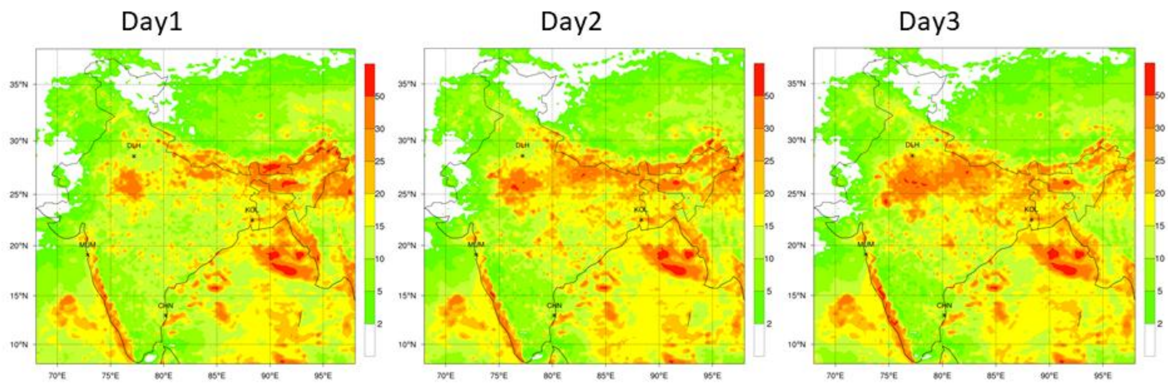

Figure 5.24 RMSE in rainfall for the month of August

In the month of August Major rainfall activity is seen over west coast, West Madhya Pradesh, East Rajasthan, East Uttar Pradesh, Bihar, Bengal and North East states. In west coast rainfall in the range of 50-100 cm is reported in August month. Figure 5.22 shows mean rainfall for the month of August in observations and WRF model forecasts of lead times from day1 to day3. Figure 5.23 and Figure 5.24 shows mean error and RMSE in rainfall respectively for the month of August. Here also over estimation of rainfall can be seen over west coast and North East India. day1 forecast shows more closer match with observations compared to day2 and day3 forecast. In day1 forecasts RMSE values are less in comparison to forecasts of longer lead times.

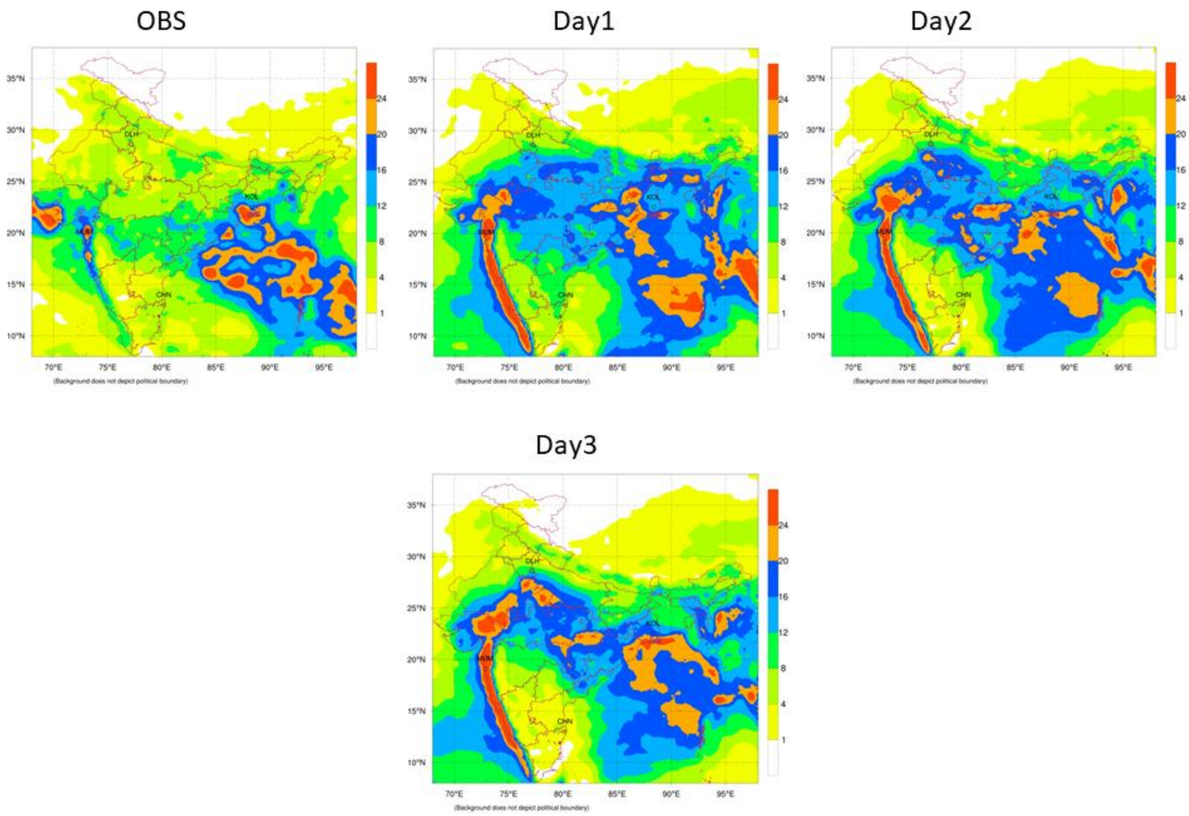

Figure 5.25 Mean rainfall in the month of September

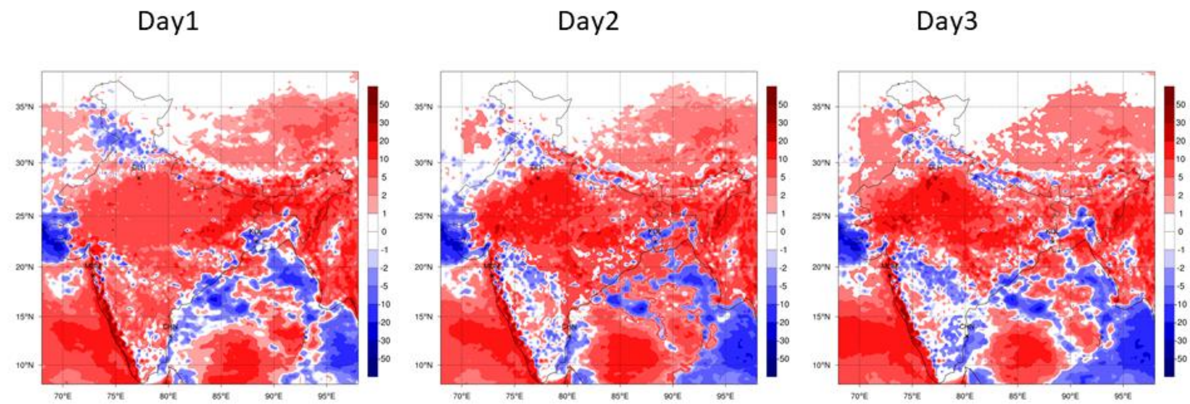

Figure 5. 26 Mean error in rainfall for the month of September

In September Major rainfall activity is reported over west coast of India especially over Gujarat and Konkan and Goa, Madhya Maharashtra, Marathwada, Chhattisgarh, Odisha, West Bengal, some parts of coastal Andhra-Pradesh, Telangana, East Uttar Pradesh, North East states, Punjab, Himachal Pradesh and Uttarakhand. Figure 5.25 shows mean rainfall for the month of September in observations and WRF model forecasts of lead times from day1 to day3. Figure 5.26 and Figure 5.27 shows mean error and RMSE in rainfall respectively for the month of September.

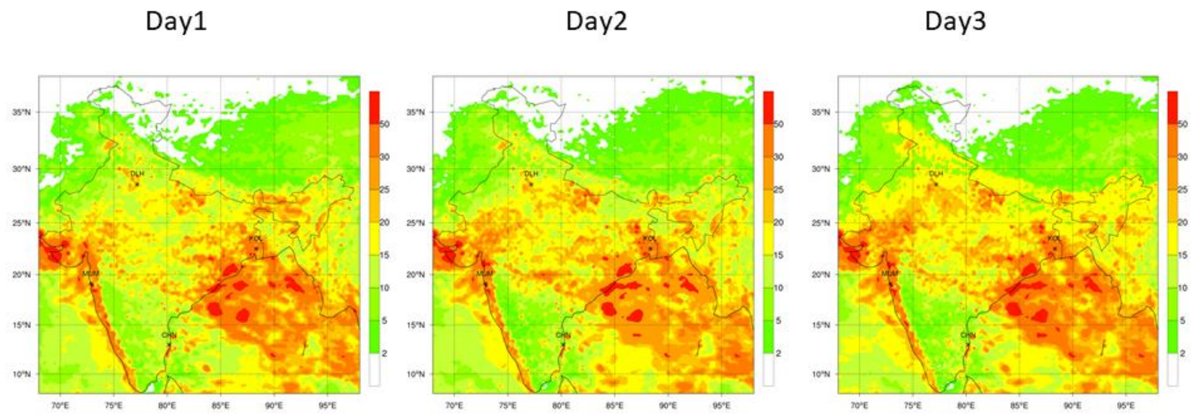

Figure 5.27 RMSE in rainfall for the month of September

As seen in other months, rainfall is over estimated in west coast and parts of North East India in September also. Rainfall is overestimated in parts U.P., Madhya Pradesh, Chattisgarh, Odisha and West Bengal also in this month which can be seen in day1 forecast also. Various categorical skill scores are computed to evaluate model performance in forecast of rainfall in different rainfall categories and different spatial domains. The different rainfall categories are defined on the basis of the classification used in India Meteorological Department. Here Critical Success Index (CSI or threat score) and Gilbert Skill Score (GSS or equitable threat score) over seven specified spatial domains over India and entire Indian region is discussed. The details of skill scores used can be seen in the Pattanaik et al., 2021.

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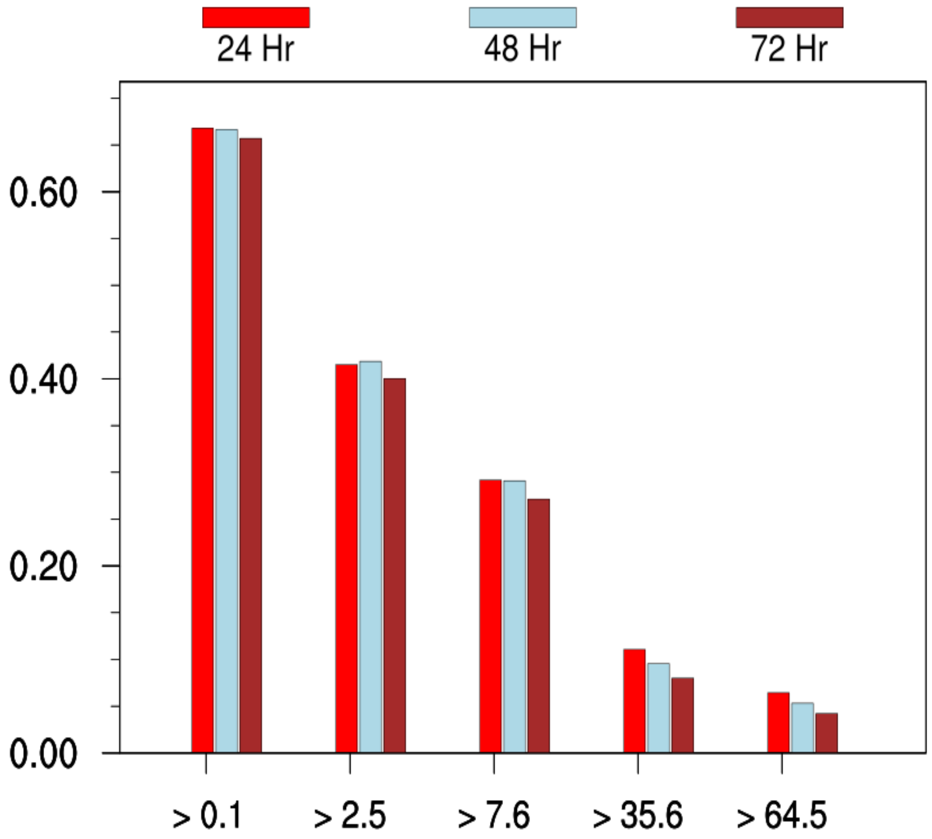

Figure 5.28 Critical Success Index (CSI) over entire Indian domain for different rainfall thresholds

Figure 5.28 shows critical success index (CSI) over Indian domain. It can be seen that CSI has good skill for lower rainfall thresholds while skill decreases considerably for higher rainfall amounts. Figure 5.29 shows Probability of Detection of "yes" events (PODY) for different rainfall thresholds over entire Indian domain. It is a measure of fraction of events that were correctly forecasted.

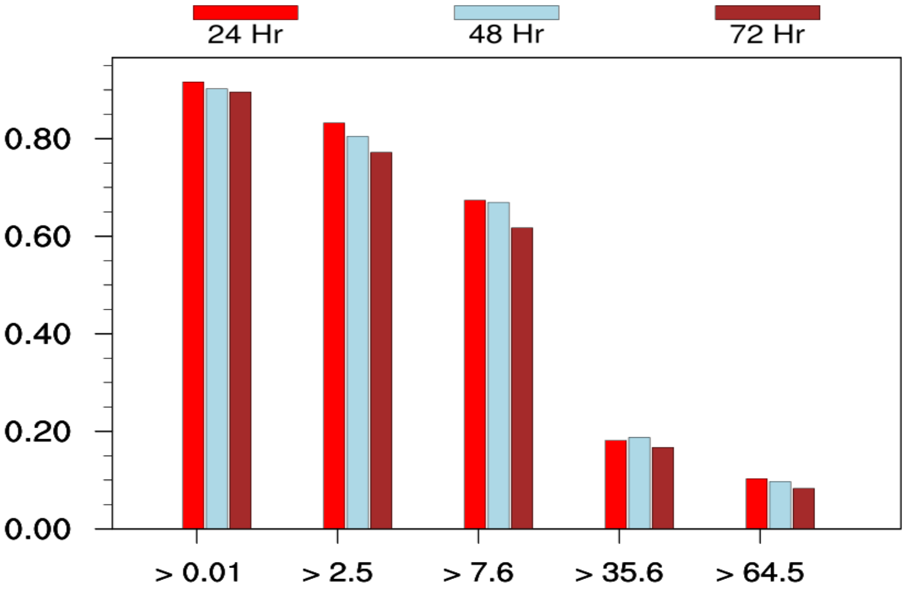

Figure 5.29 Probability of Detection of “yes” events (PODY) of rainfall forecast over Indian Domain for different rainfall thresholds

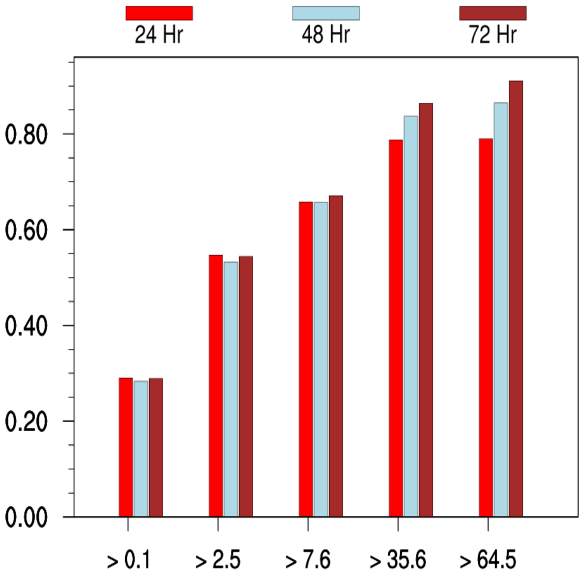

Figure 5.30 False Alarm Ratio (FAR) of rainfall forecast over Indian Domain for different rainfall thresholds

False Alarm ratio (FAR) is a measure fraction of non-events that are forecasted to be events. Figure 5.30 shows FAR of rainfall forecasted over Indian domain. FAR is greater than 0.5 for the rainfall threshold > 2.5 mm and PODY is greater than 0.5 for rainfall amount < 35.6 mm.

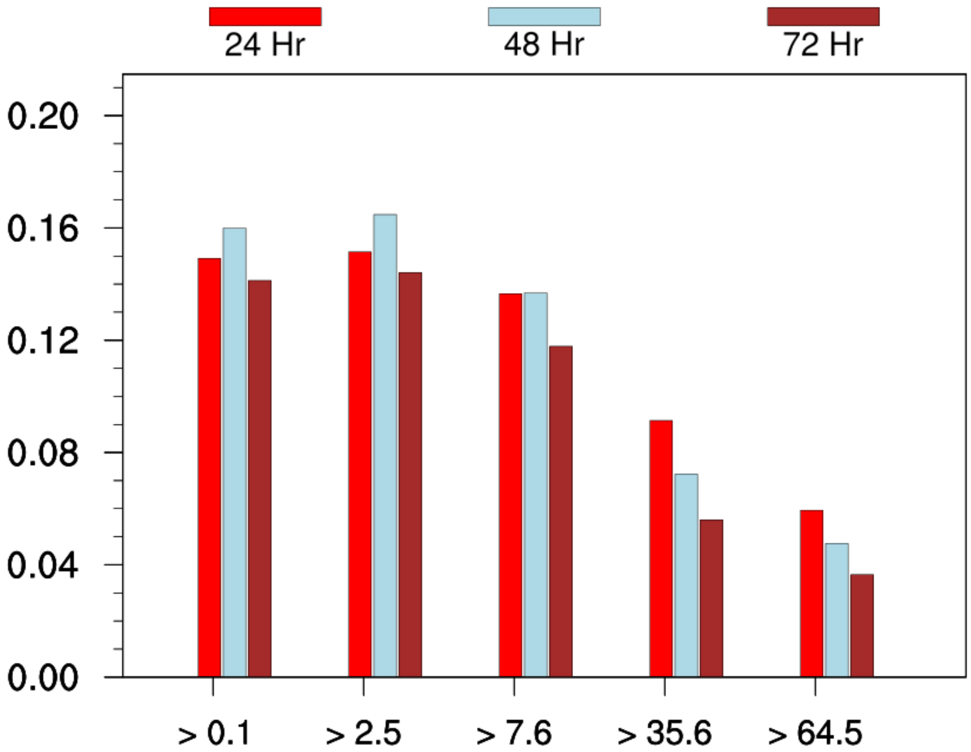

Figure 5.31 Gilbert Skill Score (GSS) of rainfall forecast over Indian domain

Gilbert Skill Score (GSS) of rainfall forecast over Indian domain is shown in Figure 5.31. GSS score is in the range of 0.04 to 0.18 for different rainfall categories and decreases as the rainfall amount increases. GSS score is greater than 0.1 for the rainfall amount less than 35.6 mm. Skill scores are computed over different spatial domain to find out regional biases. Figure 5.32 shows CSI skill scores over different spatial domains over India. In all the regions CSI scores are greater than 0.2 for the rainfall amounts less than 35.6 mm and for higher amount of skill scores are poor. Figure 5.33 shows GSS skill scores over different spatial domain over India. GSS scores > 0.1 is seen over Kerala for the rainfall amount less than 35.6 mm and in NW India for rainfall amount less than 7.6 mm. In west coast GSS of 0.1 is seen for the rainfall amount in the range 2.5 mm to 35.6 mm. in all other regions GSS value is less than 0.1.

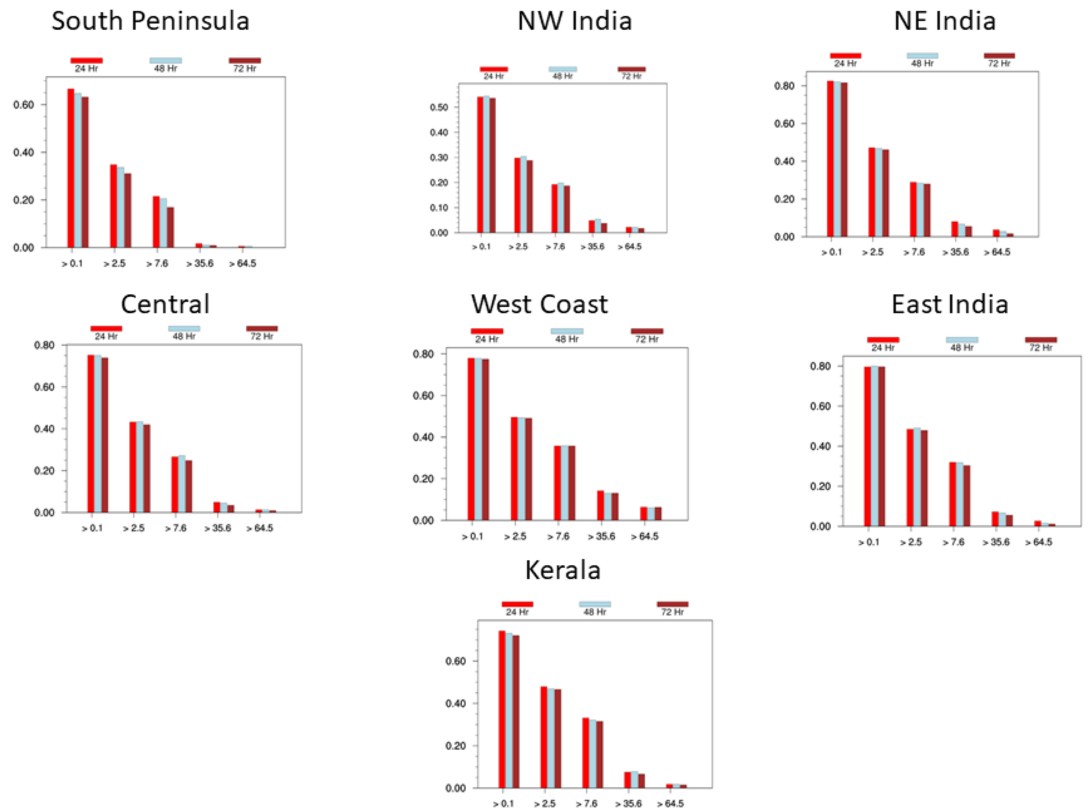

Figure 5. 32 Critical Success Index (CSI) scores rainfall forecast over different spatial domains over India

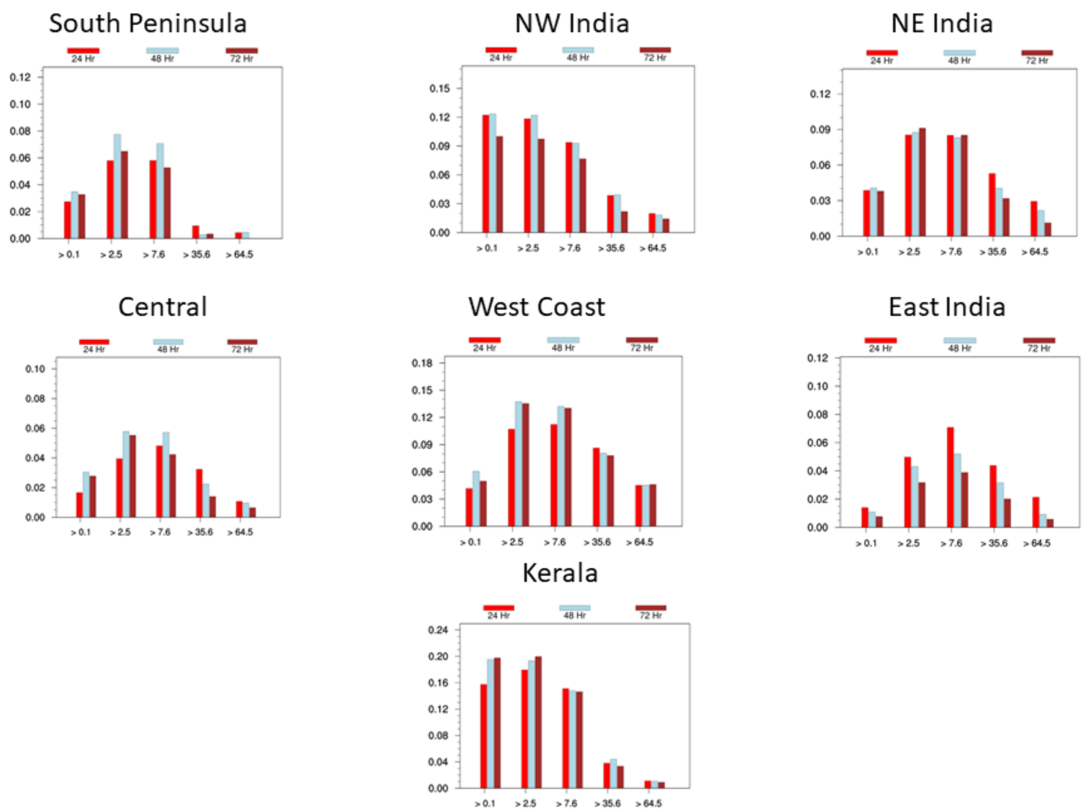

Figure 5.33 Gilbert Skill Score (GSS) of rainfall forecast over different spatial domains over India

IMD-WRF model forecast is evaluated during the South West monsoon period of 2021. Model is able to represent general characteristics of rainfall in all the months. There is a systematic overestimation of rainfall over West coast of India and North East India in all the months. It is seen that model has good skill in the forecast of light to moderate rainfall while in forecast of heavy rainfall model skill is poor. In mean characteristics of rainfall day1 forecast show better match with observed rainfall than forecasts of longer lead times which is more evident in the months from June to August.

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Mitra A K, Bohra A K, Rajeevan M and Krishnamurti T N (2009) Daily Indian precipitation analyses formed from a merge of rain-guage with TRMM TMPA satellite derived rainfall estimates; J. Meteorol. Soc. Japan, 87A, 265–279

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VERIFICATION OPERATIONAL EXTENDED RANGE FORECAST DURING SOUTHWEST MONSOON 2021

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Abstract

The real time extended range forecast during 2021 southwest monsoon season has captured very well, the different phases of monsoon like the onset phase of monsoon during June, active and weak phase of monsoon and its transition from one to other during July and August and also the active phase of monsoon in September leading to the delayed withdrawal of monsoon from northwest India.

The ERF performance for the entire monsoon season of 2021 for 18 weeks period show very skilful result up to 4 weeks with the Correlation Coefficient (CC) between forecast and observed rainfall departure is found to be significant up to 4 weeks. Over the homogeneous regions it is observed that the CC is significant (95% level) between forecast and observed rainfall departure over the CE India and NW India for forecasts up to three weeks. However, the CC is significant only in week 1 forecast over the NE India and SP India. The monsoon forecast at met-subdivision and district level is also prepared during monsoon 2021 for application in Agriculture in terms of above normal, normal and below normal rainfall forecasts. The forecast for two weeks at met-subdivision and district level is very useful for application in Agriculture.

6.1. Introduction

Extended range forecast (ERF) covering the time scale from one week to about a month in the tropics is one of the most challenging tasks in atmospheric sciences. It fills the gap between medium-range weather forecasting and seasonal forecasting. The ERF time scale is certainly a difficult time range of weather forecasting, as the timescale is sufficiently long so that much of the memory of the atmospheric initial conditions is lost andon the other hand, monthly mean time average is not large enough for the atmospheric signal associated with the ocean anomalies to emerge over the atmospheric noise. Though the seasonal forecast of monsoon has its own relevance for the policy maker the forecast of monsoon in intermediate time scale are critical for the optimization of planting and harvesting. Thus, the forecasting of monsoon break in the extended range time scale, 2 to 4 weeks in advance is of great importance for agricultural planning (sowing, harvesting, etc.), which can enable tactical adjustments to the strategic decisions that are made based on the longer-lead seasonal forecasts and also will help in timely review of the prevailing monsoon conditions for providing outlooks to farmers.Several analyses have shown that sub-seasonal variability of monsoon has two preferred locations on a broader spatial scale, a strong continental convergence zone associated with convection over the land (continental) region (between 10°-25° N) and the other over the eastern equatorial Indian Ocean. The intra-seasonal variability can be defined as the see-saw pattern of the two convergence systems oscillating out of phase with one another. The oscillation is accompanied by a northward phase propagation of rainfall and other circulation feature anomalies. Hence, monsoon intra-seasonal oscillation (MISO) is associated with an explicit northward propagation of positive or negative precipitation (or convection) anomalies. Such oscillations bring a sequence of active monsoon and break monsoon situation, which is spells of dry and wet conditions, that often lasts for one to two week or more. Sub-seasonal variability of monsoon rainfall has dominant variance associated with 30-60day periodicity, and has a common mode of variability with the seasonal mean, which is hypothesized to be strengthening (weakening) the seasonal mean in its active (break) phases and the large scale structure of active/break phases, 30-60 day mode and seasonal mean are often similar.

Forecasting of intra-seasonal oscillations and the synoptic variability is a great challenge and it is an integral part of India Meteorological Department's operational forecasting strategy. The forecast of Intra-seasonal oscillations provide forewarning and outlook in different time scales and hence it is important for several stakeholder applications.It is not only the agriculture sector which is benefited from the proper outlook of extended range forecast, a skilfulextended range forecast can also be very useful for reservoir operation in managing floods during the monsoon season. Pattanaik and Das (2015)have recently demonstrated usefulness of extended range forecast in a pilot study over the Mahanadi River basin in Odisha in case of 2011 flood. Another very recent study has also indicated how the bias corrected ERF rainfall at river basin scale can improve the raw ERF during the monsoon season over India for reservir operation (Praveen et al., 2022). In the present article the performance of operational ERF over India evaluated during the southwest monsoon season from June to September, 2021 is documented.

6.2. Operational ERF system of IMD

At present the ERF system at IMD is running operationally once in a week on every (Wednesday) and the forecast is generated for 4 weeks starting from subsequent Friday to Thursday and so on. The current operational ERF modelling system is a suite of models at different resolutions based on the CFSv2 coupled model adopted from NCEP in Fig. 6.1. The operational suite is ported in ADITYA HPCS at IITM Pune for day-to-day operational run. As demonstrated in Fig. 6.1, the Multi-model ensemble (MME) out of the above 4 suite of models are run operationally for 32 days based on every Wednesday initial condition with 4 ensemble members (one control and 3 perturbed) each for CFSv2T382, CFSv2T126, GFSbcT382 and GFSbcT126. The oceanic component is the GFDL

Modular Ocean Model V.4 (MOM4). The operational suite of models consists of (*i*) CFSv2 at T382 (≈ 38 km) (*ii*) CFSv2 at T126 (≈ 100 km) (*iii*) GFSbc (bias corrected SST from CFSv2) at T382 and (*iv*) GFSbc at T126 with 4 members each (Total 16 members). This is based on the Ensemble Prediction System (EPS) of IITM developed by Abhilash*et al.* (2014b) and Abhilash*et al.* (2015). For 2021 operational forecast the hindcast run is performed for 18 years (2003 to 2020) as shown in Fig. 6.1.The average ensemble forecast anomaly of all the 4 set of models runs of 4 members each (total 16 members) based on every Wednesday is calculated by subtracting corresponding 15- year model hindcast climatology on every Thursday, which is valid for 4 weeks for days 3-9 (week1; Friday to Thursday), days 10-16 (week2; Friday to Thursday), days 17-23 (week3; Friday to Thursday) and days 24-30 (week4; Friday to Thursday). This ERF system has the capability of predicting active-break cycle of monsoon which can be used for various applications.

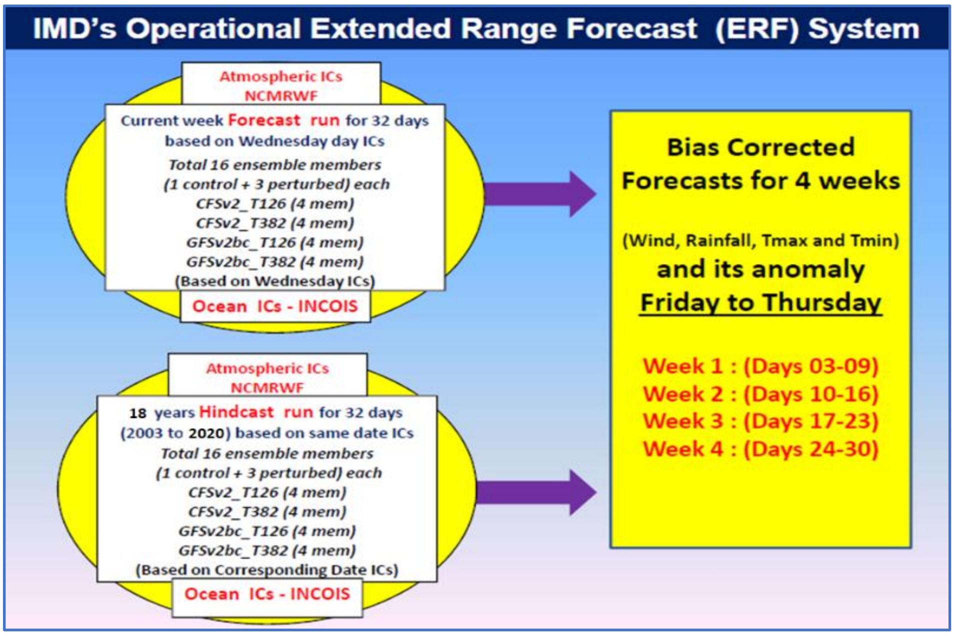


Fig. 6.1: IMD's Operational Extended Range Forecast (ERF) System

The model was initially developed at IITM (Sahai*et al.*, 2013; Sahai*et al.*, 2015), which was run using the atmospheric and oceanic initial conditions available from NCEP once in every 5 days with forecast for 4 pentads. However, three major changes were carried out before it is implemented in IMD curing 2016 such as the hindcast and forecast runs are carried out with atmospheric and oceanic initial conditions available from NCMRWF and INCOIS respectively and not from NCEP. Secondly, the forecast day was fixed on Wednesday of every week and not at the interval of 5 days. Finally, the outputs are prepared for 4 weeks and not the pentads. The evolution of operational ERF system used in IMD since 2008 is discussed in the review paperby Pattanaik*et al.*, (2019).

6.3. Verification of Extended Range Forecast during monsoon 2021

The monsoon rainfall over India during 1 June to 30 September 2021 has been 87.0 cm against long period average of 88.0 cm based on data of 1961-2010 [99% of its Long Period Average (LPA)] with the monthly rainfall over country as a whole was 110%, 93%, 76% and 135% of LPA during June, July, August and September respectively.

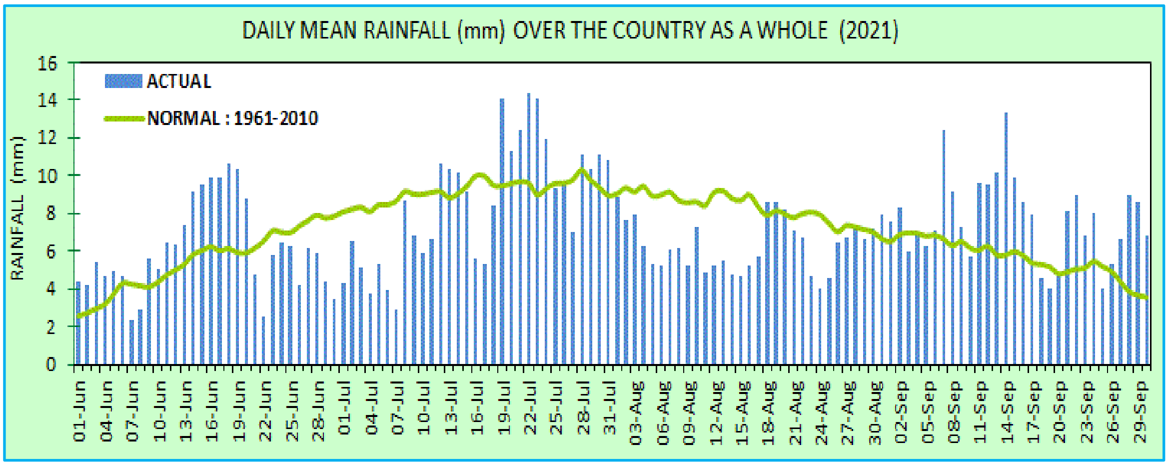


Fig. 6.2: Daily actual and normal rainfall over India during June to September, 2021

The daily monsoon rainfall over the country as a whole along with the normal rainfall is shown in Fig. 6.2. It may be mentioned here that the formation and movement of the cyclone TAUKTAE, over Arabian Sea (during 14-19 May) and severe Cyclonic storm “YAAS” over Bay of Bengal (during 23 to 28th May) helped to increase cross equatorial flow and the onset of monsoon. Subsequent featuresfavoured timely advance and monsoon covered entire country over many regions. However, monsoon cover entire country by 13thJuly against normal date of 8thJuly. In July, the country received slightly below normal rainfall (94% of LPA). The weak monsoon in July was mainly due to absence of any major monsoon disturbance over Bay of Bengal. Absence of such major systems in July also caused the weak monsoon trough. The monsoon trough lay to the north of the normal position or close to the foot hills of Himalayas on many days. It resulted in frequent and prolonged floods over north-eastern India, Bihar and adjoining areas of east Uttar Pradesh. At the same time, major parts of central India received deficient rainfall. During August, many unfavourable features of monsoon appeared resulting in deficient rainfall for the country (76%). Negative Indian Ocean Dipole unfavourable for Indian monsoon prevailed during this month. Also, the absence of formation of monsoon depression and a smaller number of low pressure area (16-18 & 28-30 August) over Bay of Bengal caused this rainfall deficiency. Normally two monsoon depressions and two low pressure area forms in the month of August. Most of the days monsoon trough was located north of its normal position which cause subdued rainfall over Central Indian Region. Most of the days Madden JulianOscillation (MJO) was in the phase 8, 1 and 2 which are unfavourable for monsoon rainfall activity. Also, there was less number of west Pacific Typhoon activities. Normally remnants of westward moving typhoons help to form Low Pressure Systems (LPS) over Bay of Bengal. In September, the country as whole received excess rainfall due to many favourable conditions for the monsoon. The negative Indian Ocean dipole weakened during the month of August and at the same time the cold anomaly in the equatorial Pacific strengthened. There was a monsoon depression and a cyclonic stormformed in the month of September. During, most of the days MJO was in the phase 3, 4 and 5 which are favourable for monsoon rainfall activity and low pressure system. More West Pacific Typhoon activity and the remnants of these westward moving systems helped to form LPS over Bay of Bengal. All the LPSs followed west/north-westward track causing good rainfall activity, especially over central India and adjoining areas.

The extended range forecast of rainfall during different phases of monsoon with forecast lead time of three weeks are shown in Fig. 6.3 to Fig. 6.7 for the target weeks of 11-17 June, 16-22 July, 2021, 06-12 August, 13-19 August and 24-30 September, 2021 respectively. Out of these five weeks, the target week from 11-17 June and 16-22 July are relatively active weeks of monsoon and the two weeks in August from 06–19 August are weaker monsoon phase and the last week of September from 24-30 September is the active monsoon period. As shown in Figs. 6.3 to 6.7 the ERFs have captured the intra-seasonal variability very well with 2 to 3 weeks lead time for all the target weeks covering active, weak and transition phases of monsoon as mentioned above. The active phase of monsoon during 10-16 September as shown in Fig. 6.7 leading to delayed withdrawal of monsoon from northwest India was well predicted in the ERF with 3 weeks lead time.

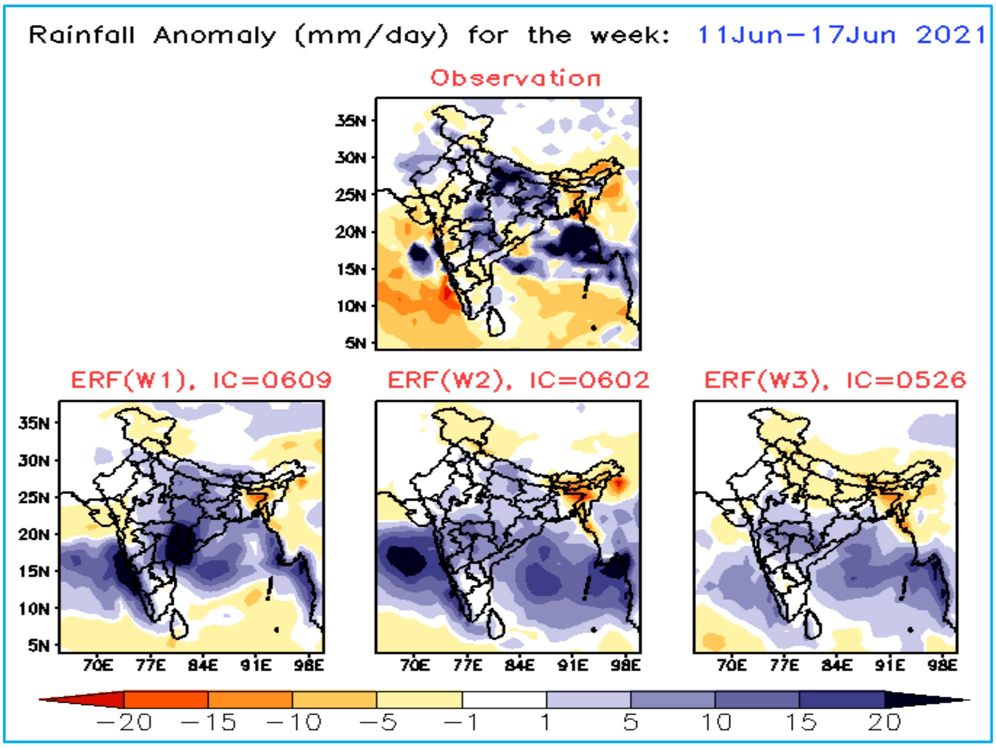


Fig. 6.3 :Observed rainfall anomaly for the target week of 11-17 June 2021 with extended range forecast rainfall with three weeks lead time (ICs of 09 June, 2 June and 26 May, 2021).

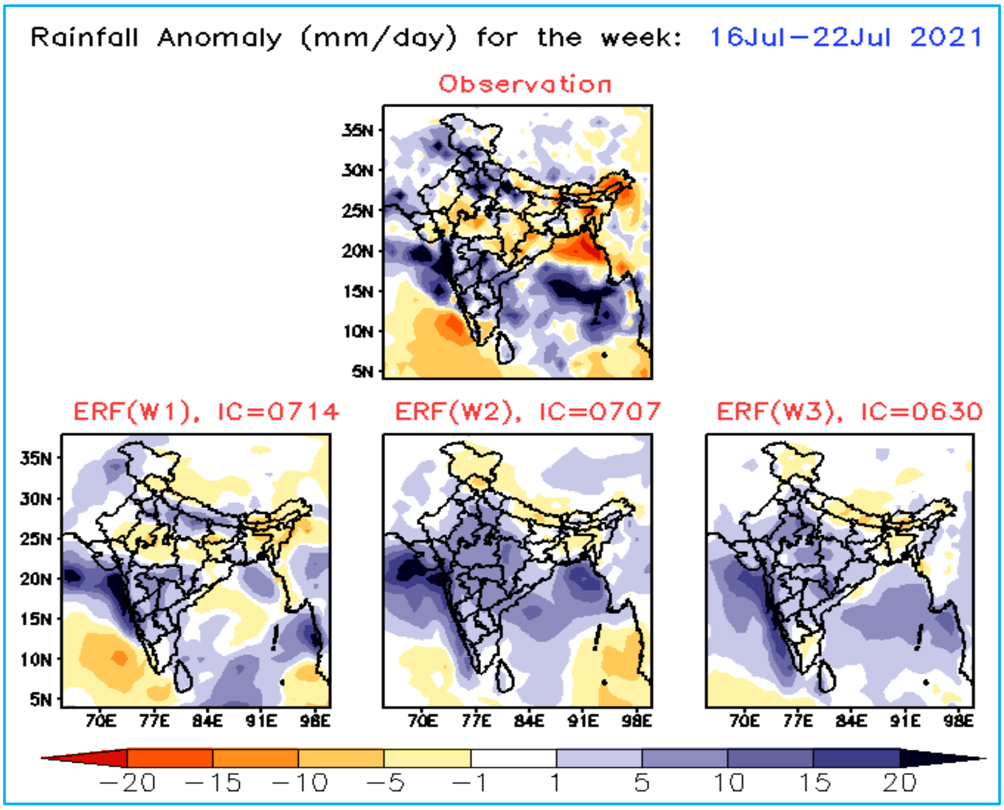


Fig. 6.4 : Observed rainfall anomaly for the target week of 16-22 July 2021 with extended range forecast rainfall with three weeks lead time (ICs of 14 July, 07 July and 30 June, 2021)

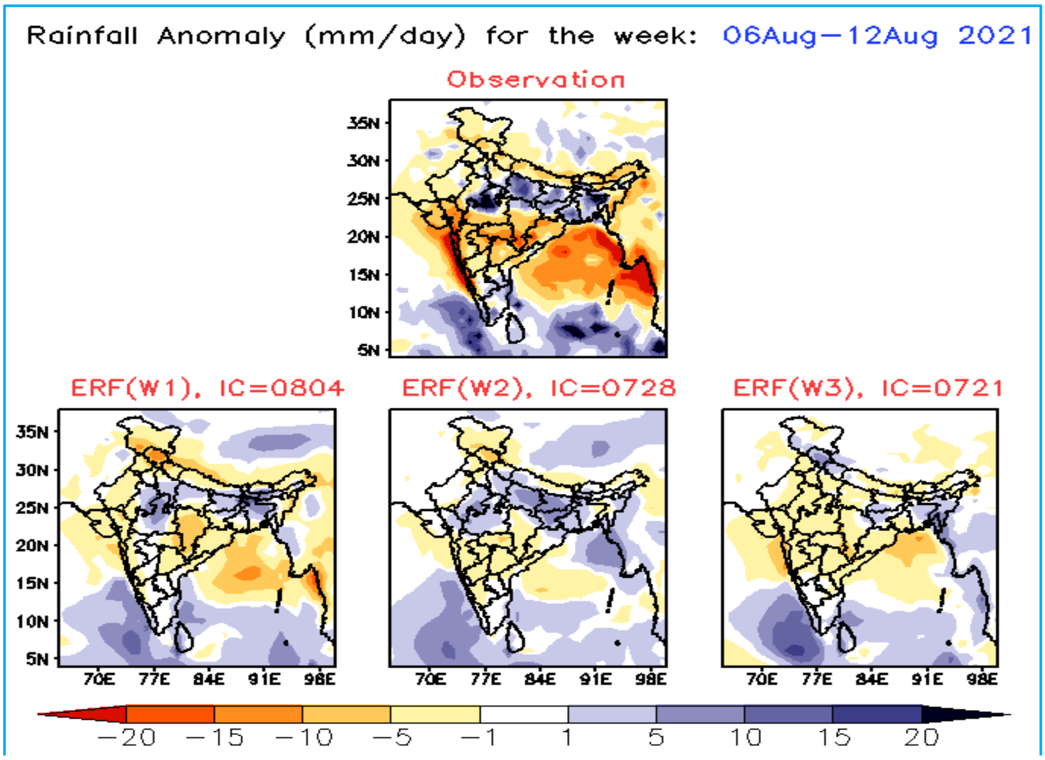


Fig.6.5 : Observed rainfall anomaly for the target week of 06-12 August, 2021 with extended range forecast rainfall with three weeks lead time (ICs of 04 Aug, 28 July and 21 July, 2021)

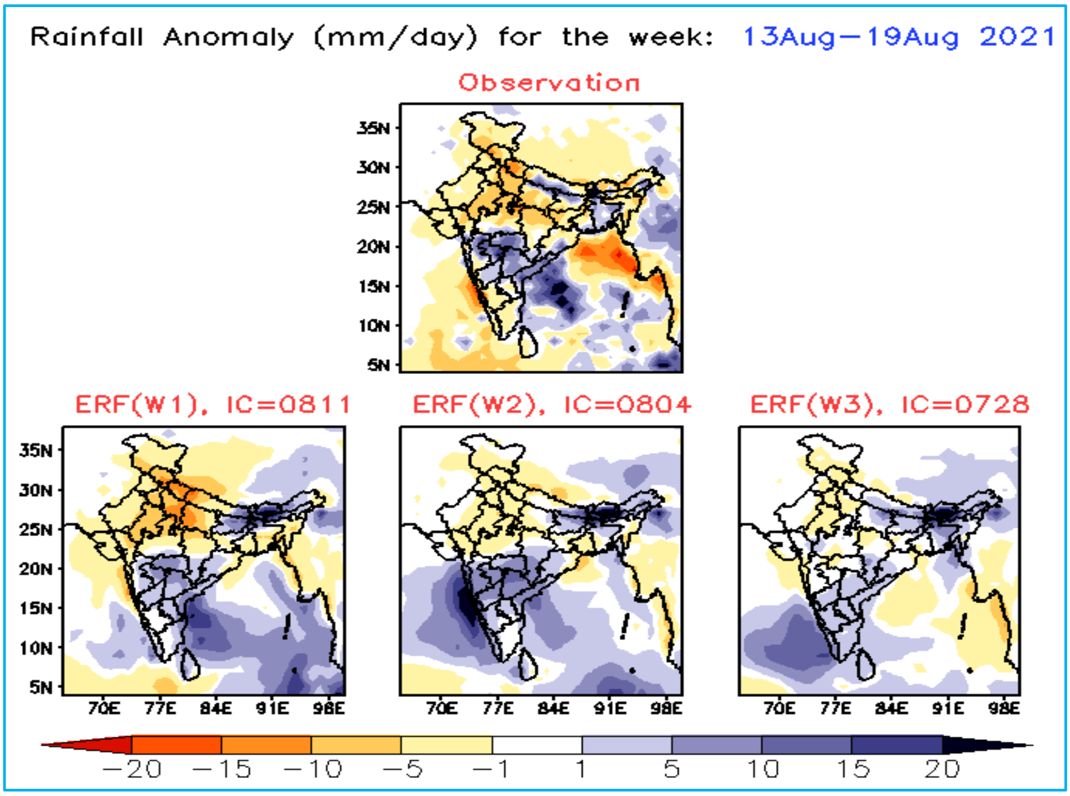


Fig. 6.6: Observed rainfall anomaly for the target week of 13-19 August, 2021 with extended range forecast rainfall with three weeks lead time (ICs of 11 Aug, 04 Aug and 28 July, 2021)

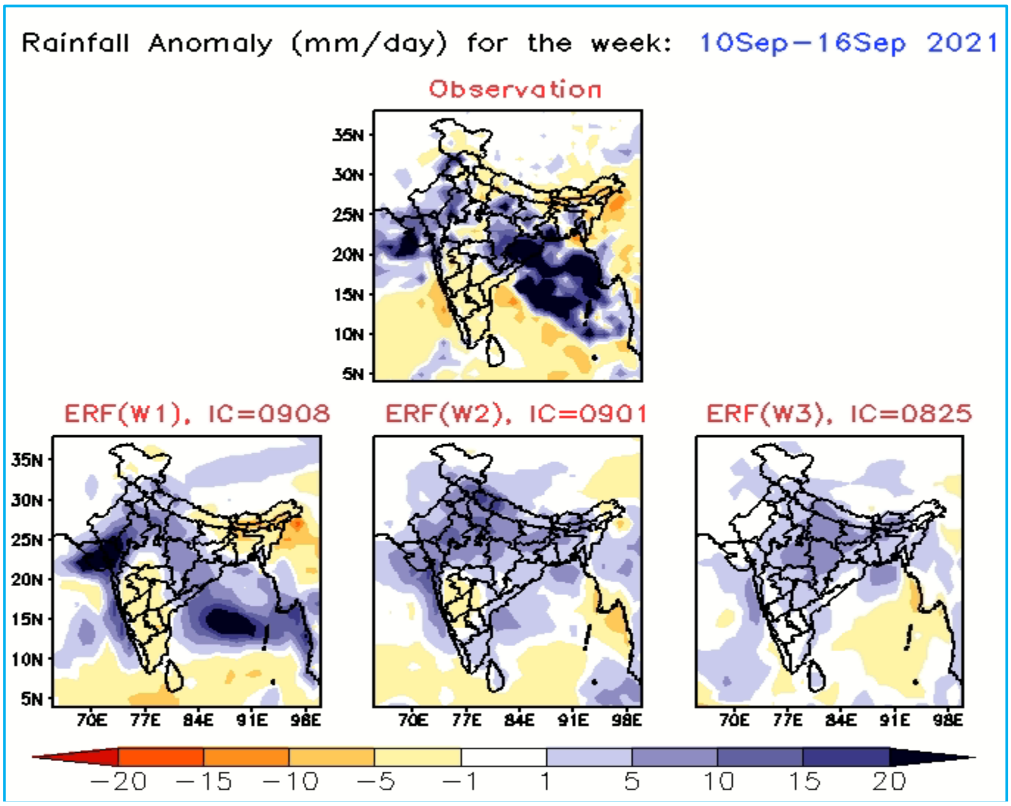


Fig. 6.7: Observed rainfall anomaly for the target week of 10-22 Sep 2021 with extended range forecast rainfall with three weeks lead time (ICs of 14 July, 07 July and 30 June, 2021)

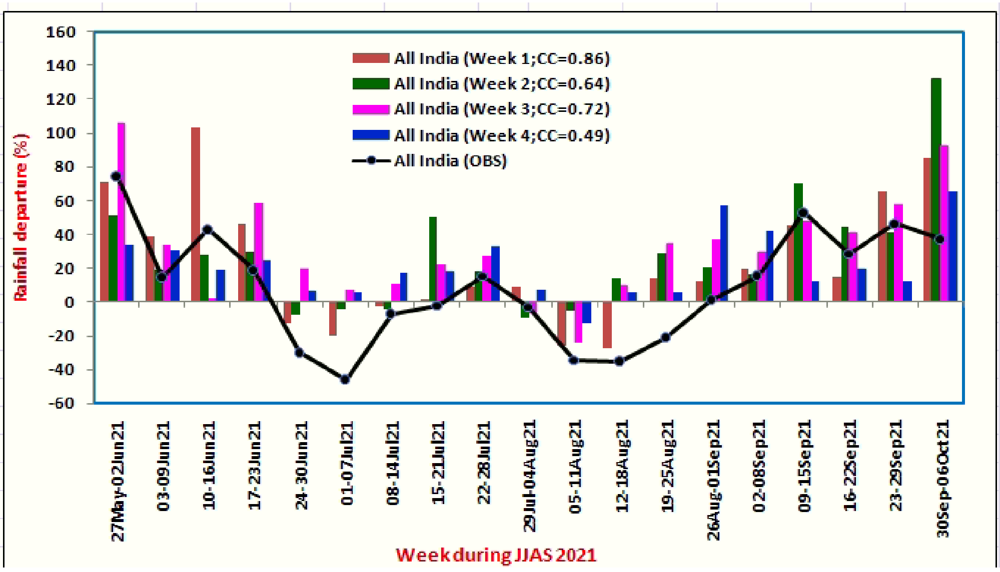


Fig. 6.8: Weekly observed rainfall departure over India along with extended range forecast rainfall up to 4 weeks during the monsoon season from June to September 2021

Quantitatively, the ERF performance for the entire monsoon season of 2021 for 18 weeks period along with observed rainfall departure is shown in Fig. 6.8. As seen from Fig. 6.8the operational ERF during 2021 monsoon season has captured the different phases of monsoon very well, with significant correlation coefficients up to 4 weeks lead time between observed and forecast rainfall departure.

6.4: Homogeneous regions, Met-subdivision/district level ERF

As seen in the above analysis the ERF could capture the active and weak phases of monsoon along with its transition from active to break phase and vice versa. However, at very smaller spatial domains the model still has the problems. In view of that it is necessary to calculate the quantitative skill at smaller spatial domains. In order to see the quantitative verification of extended range forecast over the four homogeneous regions of India and the rainfall over Monsoon Zone of India (MZI) as shown in Fig. 6.9 are considered for calculating the anomaly correlation coefficient (ACC). The four homogeneous regions of India are classified as Central India (CEI), Northeast India (NEI), Northwest India (NWI) and South Peninsular India (SPI) and the fifth zone is Monsoon Zone of India (MZI) covering mostly the central parts of India and little parts of northwest India as shown in Fig. 6.9.

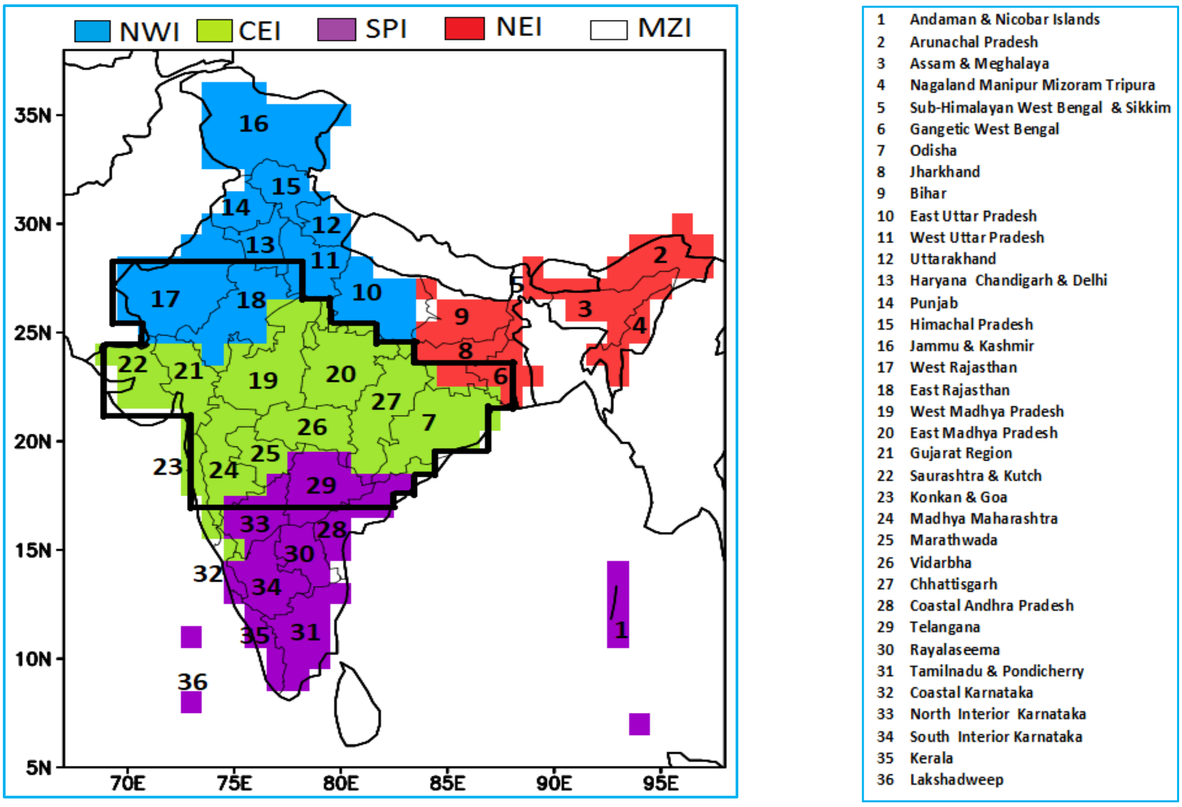
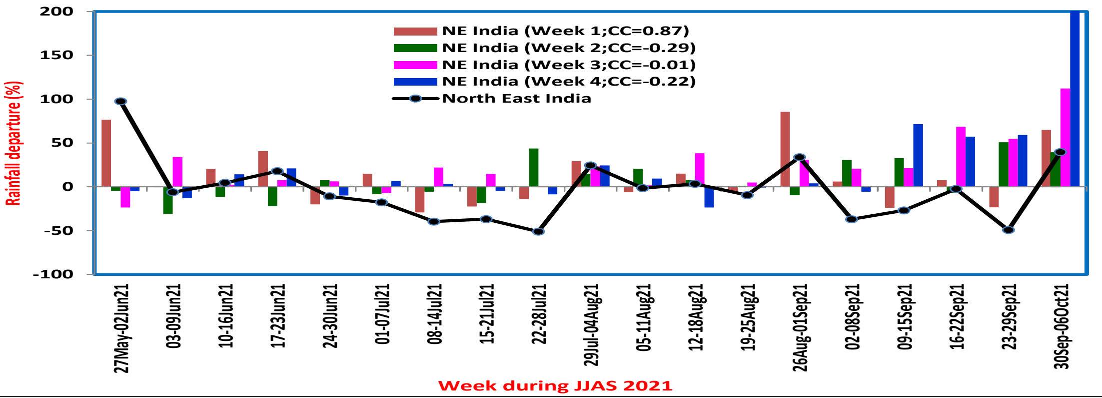


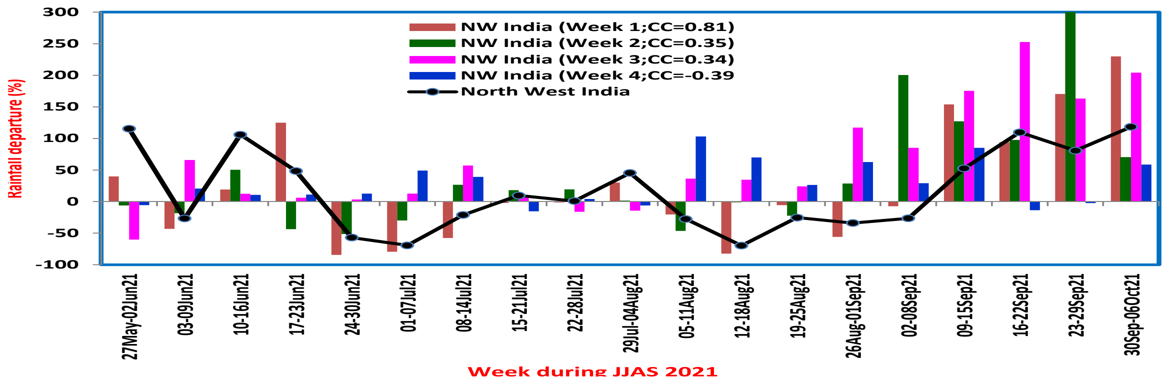
Fig. 6.9.Homogeneous regions of India, NEI - Northeast India, NWI – Northwest India, CEI – Central India, SPI – South Peninsular India and MZI – Monsoon Zone of India

Fig. 6.10shows forecast skill of real time extended range forecast for the 4 homogeneous regions of India during the southwest monsoon season 2021. It is seen that significant CC (95% level) between forecast and observed rainfall departure over the CE India and NW India is seen for forecasts up to three weeks. However, the CC is significant only in week 1 forecast over the NE India and SP India. The lower skill over NE India is basically due to the orographic rainfall over the region not predicted very well with longer lead time. Similarly, the lower skill over SP India compared to CE India and NW India is also associated with the west-coast rainfall not able to capture with sufficient lead time as it is also dominated by mountainous regions.

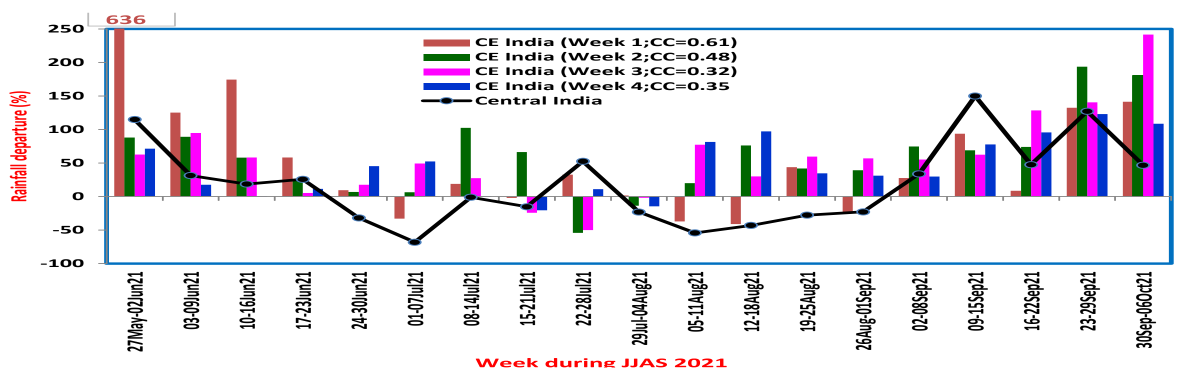
(a)



(b)



(c)



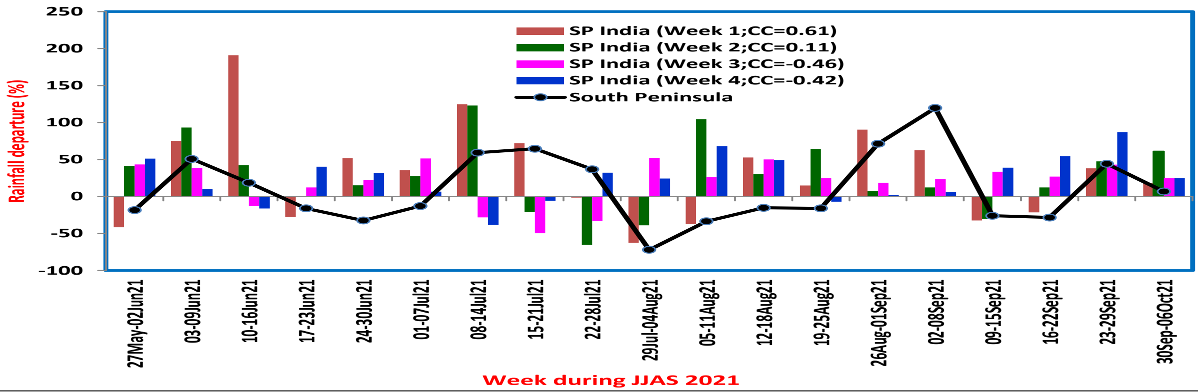


Fig. 6.10:ERF skill of monsoon rainfall during monsoon 2021 over homogeneous regions.

6.5 : Met-subdivision level forecast for application in Agriculture

The sub-division wise observed rainfall departure over different met-subdivisions of India during the transition from active to weak phase of monsoon can be seen from the daily rainfall plots over the core-monsoon zone along with departure as shown in Fig. 6.11(a-b) respectively. In order to use the extended range forecast for Agromet applications the forecast for 36 met subdivisions of India is prepared for two weeks with categorising the subdivisions as below normal, normal or above normal category depending on the rainfall departure during the week. As per the classification a met-subdivision is considered to be above normal (AN) if rainfall departure ≥ 20%; Normal (NN) if it is between +19% to -19% and Below Normal

(BN) if it is ≤ -20%. The two weeks forecast on met-subdivision level is widely used for application in Agriculture for farmers' advisory. Based on the forecast rainfall departure on met-subdivision level the two weeks forecast is prepared. The observed active to break transition of monsoon during 06-12 August to 13-19 August, 2021 can be seen in the daily observed rainfall and its departure shown in Fig. 6.11(a-b). The observed rainfall departure during this period (06-12 August to 13-19 August, 2021) can also be seen in the upper panel of the Figs. 6.5(a) and Fig. 6.6(a)respectively.

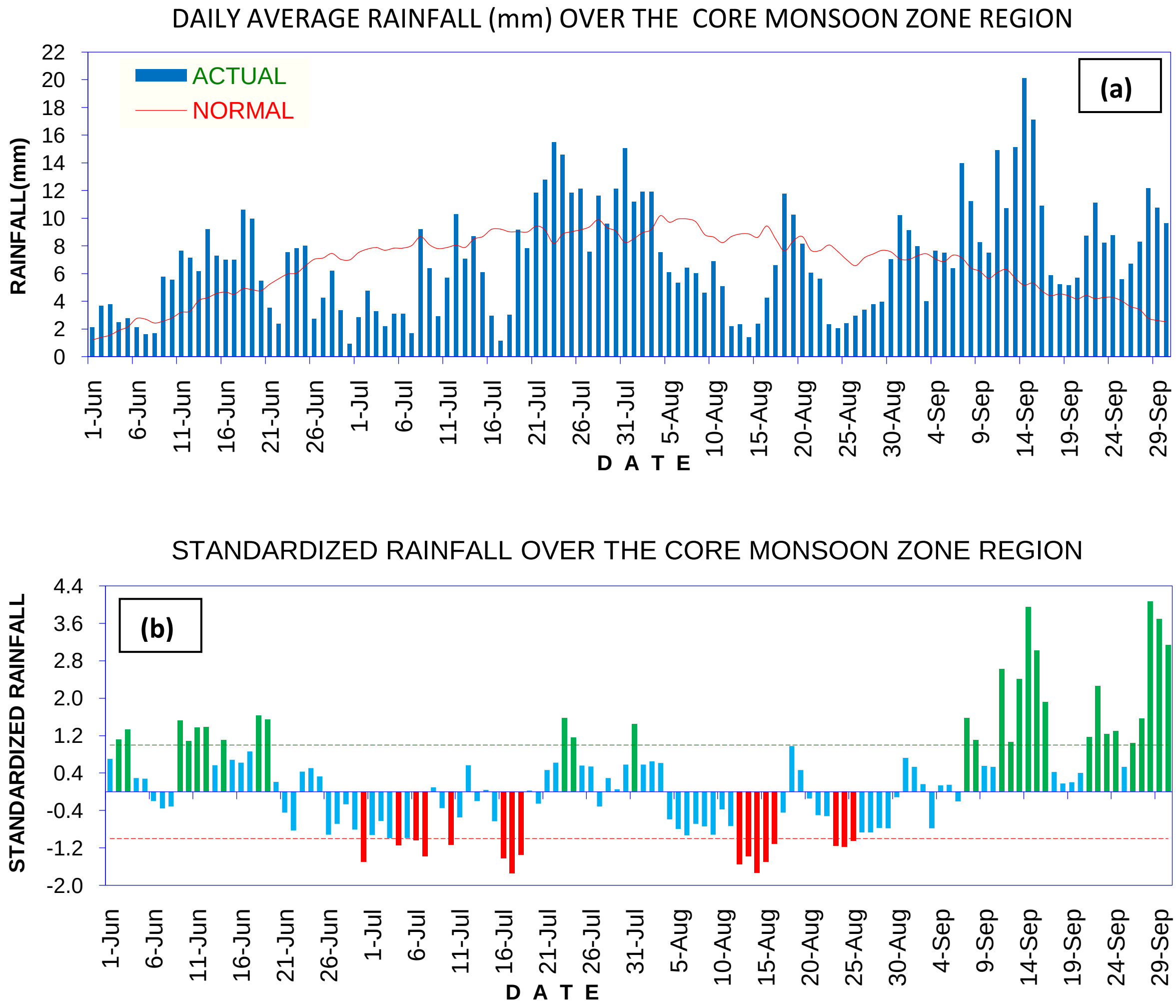


Fig. 6.11: (a) Daily average rainfall (mm) over the core monsoon zone region along with (b) standardized rainfall during the monsoon season from 1st June to 30 September, 2021.

The met-subdivision level forecast based on the initial condition of 4th August 2021 and valid for the subsequent two weeks (06-12 Aug and 13-19 Aug, 2021) are shown in Fig. 6.12(a-b) respectively. As seen from Fig. 6.12(a) most of the meteorological subdivisions in central India and south peninsula changed into below normal category in week 1 forecast. The weak phase of monsoon in terms of below normal met-subdivisions over central and northern parts of India is also seen in week 1 forecast in Fig. 6.12(b) over northwest India, however, monsoon rainfall is revived over south Peninsula India and adjoining central India during week 2 forecast valid for the period 13-19 August. Thus, the transition of monsoon from above normal to below normal is well captured in the extended range forecast, which is being used widely for Agromet advisory purpose.

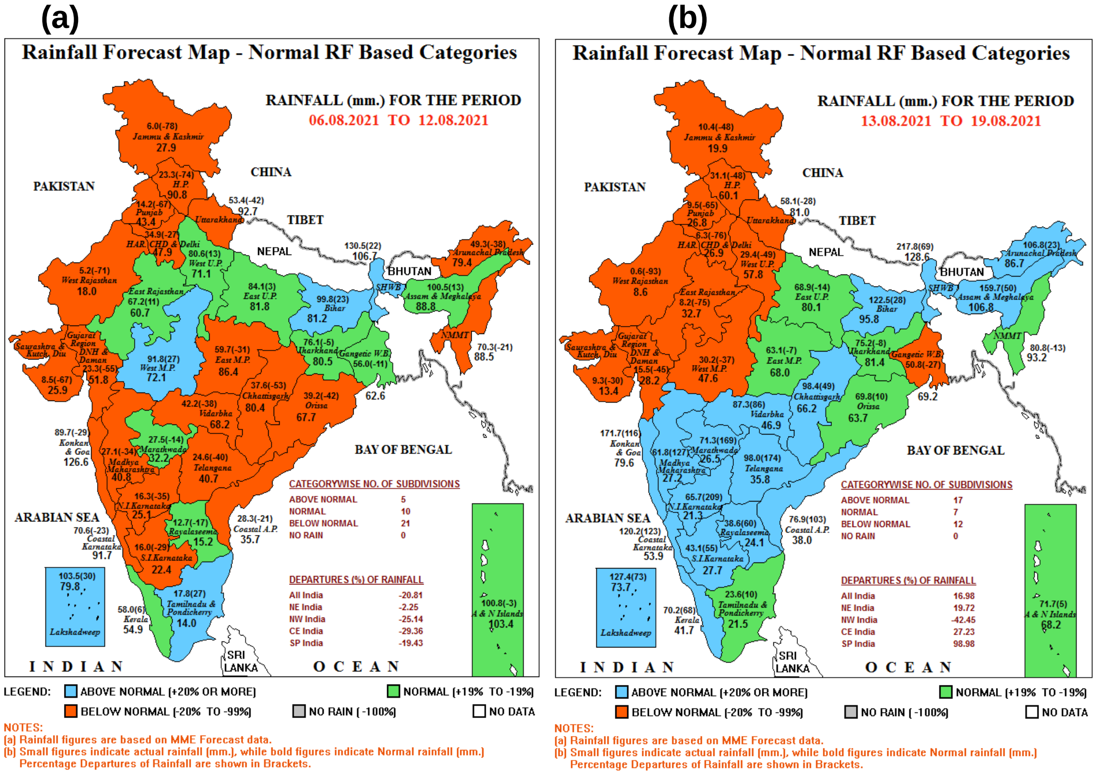
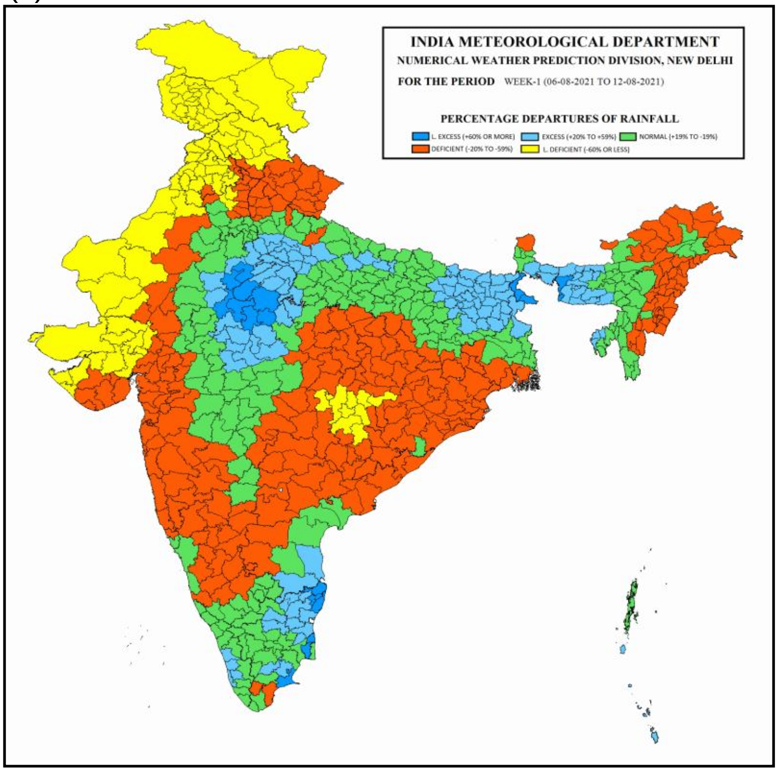


Fig. 6.12 : Met-subdivision wise forecast for two weeks based on 04 August 2021 IC and forecast for (a) 06-12 August, 2021 and (b) 13-19 August 2021.

6.6. Districts level extended range forecast

The ERF at smaller spatial scales viz., at met-subdivision level and district level are also being prepared operationally for application in agriculture. As we have seen ERF is skilful and useful for two to three weeks. In order to prepare the forecast at smaller spatial domain at district level for Agromet application, IMD is also preparing district level forecast on experimental basis in terms of above normal, normal and below normal categories. The district level forecast for two weeks based on 04 August 2021 IC and forecast for (a) 06-12 August, 2021 and (b) 13-19 August 2021 is also seen in Fig. 6.13(a-b). Like the district level forecast of rainfall the district level forecast of maximum and minimum temperature is also prepared on the experimental basis for various applications, which is available in NWP's website.

(a)



(b)

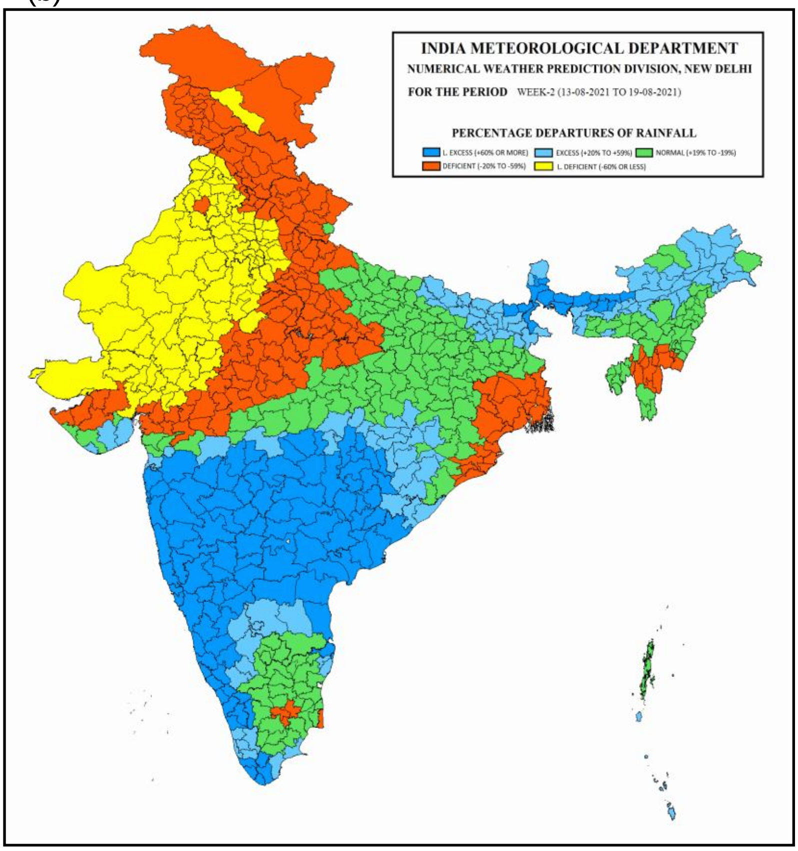


Fig. 6.13 :The district level forecast for two weeks based on 04 August 2021 IC and forecast for (a) 06-12 August, 2021 and (b) 13-19 August 2021.

6.7 Summary

The real time extended range forecast during different phase of monsoon 2021 have captured the observed intra-seasonal variability very well with 2 to 3 weeks lead time for all the target weeks covering active, weak, transition phases of monsoon and the delayed withdrawal of monsoon from northwest India. Quantitatively, the ERF performance for the entire monsoon season of 2021 for 18 weeks period show very skilful prediction with the extended range forecast of rainfall has been captured very well like the observed rainfall departure during the different phases of monsoon. Significant correlation coefficients up to 4 weeks lead time between observed and forecast rainfall departure on all India time scale is noticed. The active phase of monsoon during September leading to delayed withdrawal of monsoon from northwest India was well predicted in the ERF with 3 weeks lead time. Over the homogeneous regions it is observed that the CC is significant (95% level) between forecast and observed rainfall departure over the CE India and NW India for forecasts up to three weeks. However, the CC is significant only in week 1 forecast over the NE India and SP India.

The monsoon forecast at met-subdivision and district level is also prepared during monsoon 2021 for application in Agriculture. The two weeks forecasts based on the initial condition of 4th August 2021 and valid for the subsequent two weeks (06-12 Aug and 13-19 Aug, 2021) has clearly captured the weak phase of monsoon over central India in week 1 forecast and its revival over southern peninsula in week 2 forecasts. The same is captured both at met-subdivision and district level.

Acknowledgement

The authors are thankful to the Director General of Meteorology, Dr. M. Mohapatra for providing all facility in IMD in carrying out this research work. Thanks are also due to the IITM's ERF Group, NCMRWF and INCOIS for collaborating with IMD in enhancing the extended range forecast activity of IMD in running the coupled model.

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7

Verification Operational & Experimental Long Range Forecast during Southwest Monsoon 2021

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This chapter discusses the various operational forecasts issued by India Meteorological Department (IMD) for the monthly and seasonal rainfall over India and date of monsoon onset over Kerala for the 2021 southwest monsoon season and its verification. The chapter also discusses the dynamical seasonal forecasts generated using IMD's dynamical global forecasting system based on monsoon mission coupled forecasting system (MMCFS) and experimental obtained from various climate research centers within the country and abroad.

7.1. Introduction

Every year, India Meteorological Department (IMD) issues operational monthly and seasonal forecasts for the southwest monsoon rainfall using models based on the latest statistical techniques with useful skill (Rajeevan et al. 2007, Pai et al. 2011). This year 2021, IMD has adopted a new strategy for issuing monthly and seasonal operational forecasts for the southwest monsoon rainfall over the country by modifying the existing two stage forecasting strategy. The new strategy is based on the existing statistical forecasting system and the newly developed Multi-Model Ensemble (MME) based forecasting system. The MME approach uses the coupled global climate models (CGCMs) from different global climate prediction and research centers including IMD's Monsoon Mission Climate Forecasting System (MMCFS) model. The spatial distribution of probabilistic forecasts for tercile categories (above normal, normal and below normal) for the seasonal rainfall (June to September) over the country was also issued at the end of the previous month based on MME approach for the first time in the history of the operational seasonal forecasting in the country. In addition to that, IMD has also been making efforts to develop a separate forecast for the Monsoon Core Zone (MCZ), which represents most of the rainfed agriculture region in the country. A separate forecast for the MCZ will be more useful for agricultural planning and crop yield estimation etc. IMD will issue a separate probabilistic forecast for the MCZ, based on MME system and a new statistical model.

A brief description of IMD's operational statistical and experimental dynamical forecasting systems is discussed in this chapter along with the verification of the forecasts generated by these forecasting systems. The dynamical seasonal forecasts for the rainfall over the country using the Monsoon Mission CFS (MMCFS) as well as that from various national and international research institutes obtained by IMD as guidance before issuing operational forecasts have also been discussed.

7.2.1 Models Used

7.2.1 Statistical Ensemble Forecasting System for the Seasonal Rainfall over the Country as a Whole

The statistical ensemble forecasting system (SEFS) was used for the forecast for the season rainfall over the country as a whole. For this a set of 10 predictors (Table-7.1) <u>that</u> having stable and strong physical linkage with the Indian south-west monsoon rainfall is used. The geographical domains of the predictors are shown in the Fig.7.1. For the April SEFS, first 5 predictors listed in the Table-7.1 are used. For June SEFS, the last 6 predictors are used that include 3 predictors used for April forecast. The standard errors of the 5–parameter and 6-parameter SEFSs were taken as ±5% and ±4% respectively. A schematic diagram of the statistical ensemble forecasting system is shown in the Fig.7.2. As depicted in the Fig.7.2, the forecast for the seasonal rainfall over the country as a whole is computed as the ensemble average of best few models out of all possible models constructed using two statistical methods; multiple regression (MR) technique and projection pursuit regression (PPR) - a nonlinear regression technique. In each case, models were constructed using all possible combination of predictors. Using ‘n’ predictors, it is possible to create (2^n-1) combination of the predictors and therefore as many numbers of models. Thus with 5 (6) predictors respectively for April (June) SEFS, it is possible to construct 31 (63) models. Using sliding fixed training window (of optimum period of 23 years) period, independent forecasts were prepared by all possible models for the period 1981-2020.

Performance of the April & June SEFS for the independent test period of 1981-2020 is shown in the Fig.7.3a & 3b respectively. The RMSEs of the April & June SEFS for the period 1981-2020 are 7.46% of LPA & 7.43% of LPA respectively. The C.C. between observed and forecast rainfall of the April & June SEFS for the period 1981-2020 are 0.55 & 0.56.

Table-7.1: Details of the 10 predictors used for the new ensemble forecast system

No.	***Predictor***	***Used for forecasts in***	***Correlation Coefficient (1981-2010)***
1.	Europe Land Surface Air Temperature Anomaly (January)	April	0.39
2.	Equatorial Pacific Warm Water Volume Anomaly (February + March)	April	-0.37
3.	SST Gradient Between Northwest Pacific and Northwest Atlantic (December +January)	April	0.43
4.	Equatorial SE India Ocean SST (FEB)	April & June	0.55
5.	East Asia MSLP (FEB + MAR)	April	0.53
6.	Southeast Atlantic MSLP (Jan+Feb)	June	-0.41
7.	Tropical Central Pacific SST (May)	June	-0.45
8.	NINO 3.4 SST (MAM+(MAM-DJF) Tendency)	June	-0.41
9.	North Atlantic MSLP (APR+MAY)	June	-0.45
10.	North Central Pacific Zonal Wind Gradient 850 hPa (MAY)	June	-0.59

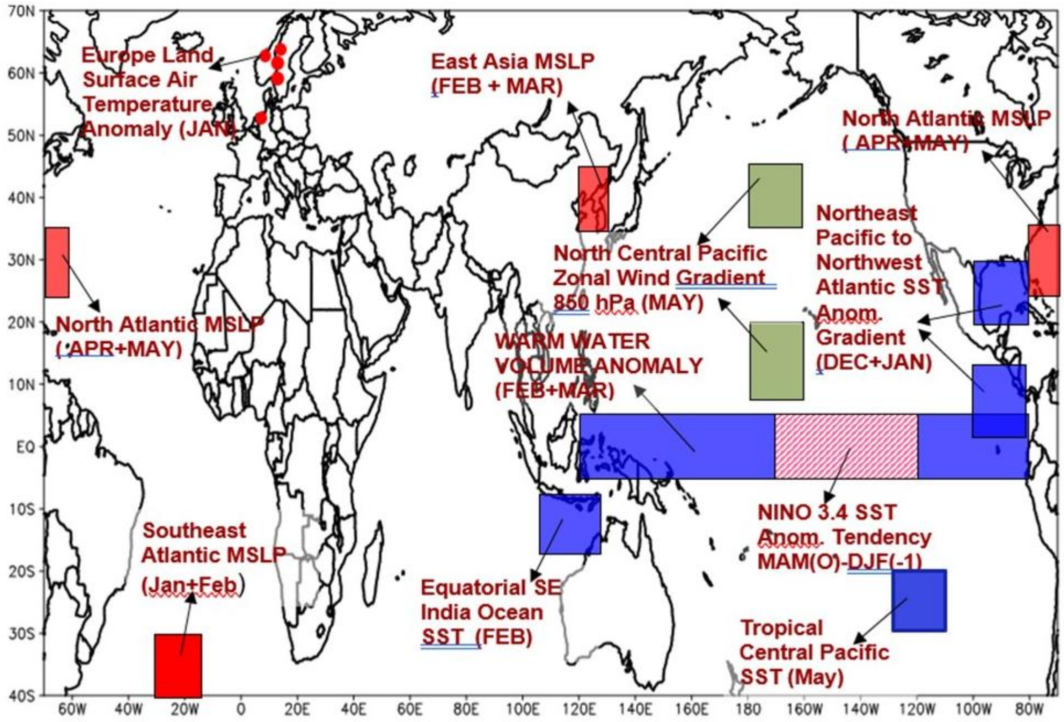


Fig.7.1. Geographical domains of the predictors used in the statistical ensemble forecasting system for the seasonal rainfall forecast over the country as a whole.

In addition to the quantitative forecast, the ensemble forecasting system has also been used to generate a five-category probabilistic rainfall forecast based on the forecast error distribution of the ensemble forecasting system. The five rainfall categories defined based on the observed data for the period 1901-2005 are deficient (< 90% of LPA), below normal (90-96% of LPA), normal (96-104% of LPA), above normal (104-110% of LPA) and excess (> 110% of LPA). The climatological probabilities of these five categories are 16%, 17%, 33%, 16% & 17% respectively. The five-category probability forecast is prepared using normal probability distribution with the ensemble average of the forecast from the ensemble forecasting system as the mean and the RMSE of the independent test period as the standard deviation. For verification purpose, the most probable category is one that has highest forecast probability compared to its climatological value. A forecast validating within the same category was considered as “correct (C)”, within one category as “usable (U)” and beyond one category as “unusable/not usable (NU)”.

The probabilistic forecast for the independent test period of 1981-2020 obtained based on the April SEFS showed that the model forecasted correct category during 10 years (23%), 1 category out during 25 years (55%) and 2 categories out during 8 years (20%). The corresponding probabilistic forecast obtained based on the June SEFS showed that the model forecasted correct category for 12 years (30%), 1 category out for 19 years (48%) and 2 categories out for 9 years (23%). The 5 category probability forecasts based on the April and June SEFS for the 2021 monsoon season are given in the Table-7.3.

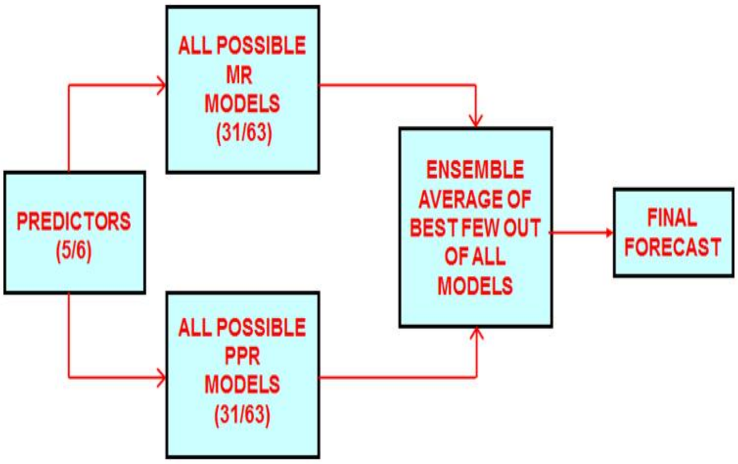


Fig.7.2. A Schematic diagram of the new ensemble forecasting system for the monsoon season rainfall over the country as a whole. The average of the ensemble forecasts from best out all possible MR (multiple regression) and PPR (projection pursuit regression) models gives the final forecast.

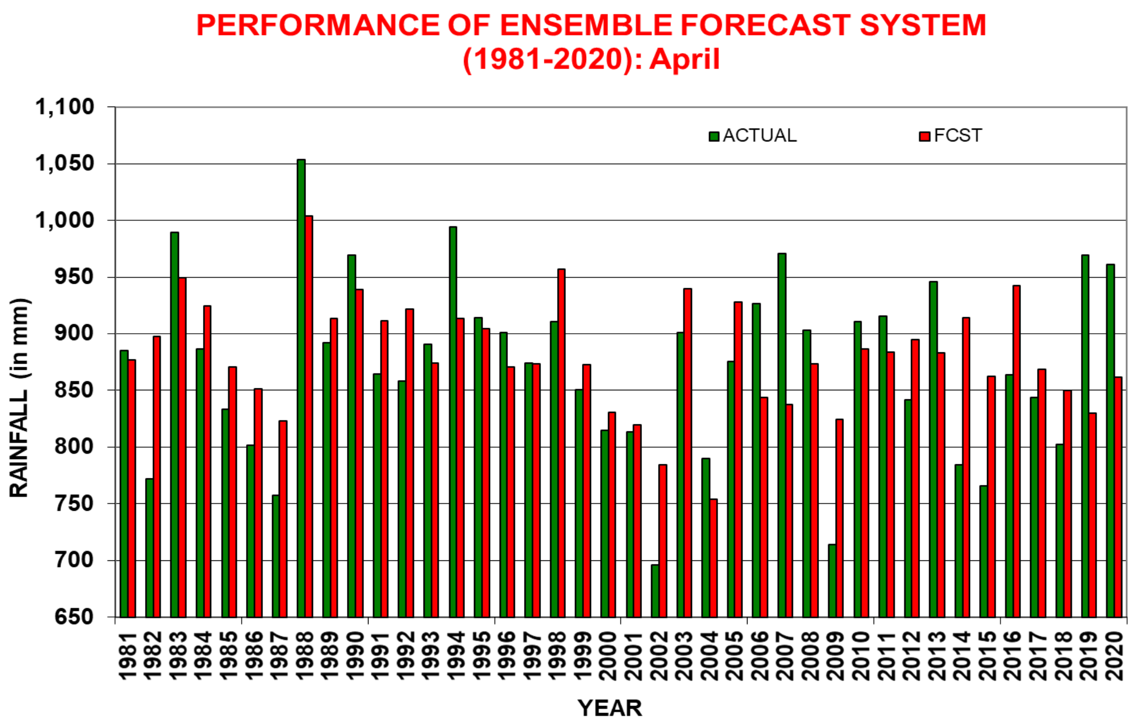


Fig.7.3a: Performance of the April ensemble forecasting system for the seasonal rainfall over the country as whole for the period 1981-2020.

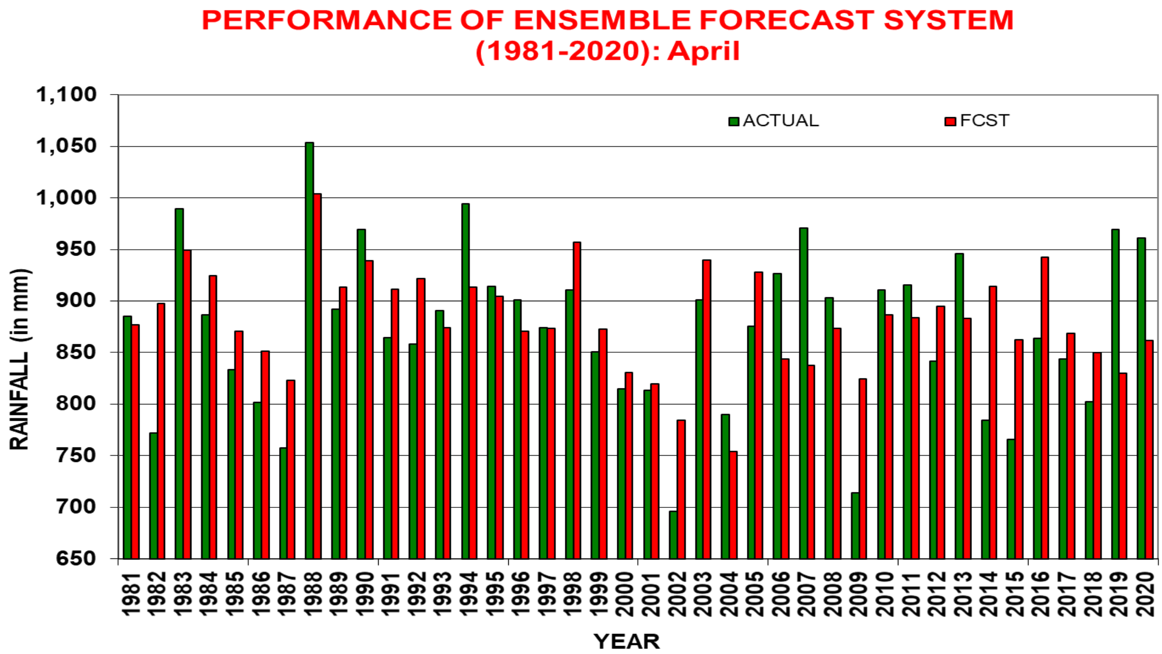


Fig.7.3b: Performance of the June ensemble forecasting system for the seasonal rainfall over the country as a whole for the period 1981-2020.

Category	Rainfall Range (% of LPA)	Forecast Probability (%)		Climatological Probability (%)
		April SEFS	June SEFS	
Deficient	Less than 90	**14**	**8**	16
Below Normal	90 - 96	**25**	**18**	17
Normal	96 -104	**40**	**40**	33
Above Normal	104 -110	**16**	**22**	16
Excess	more than 110	**5**	**12**	17

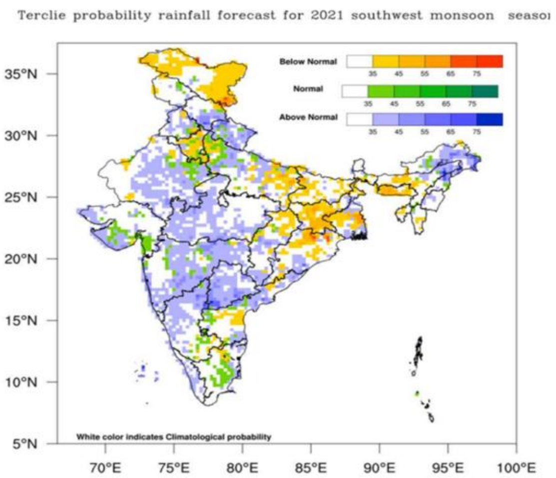
Table 7.3: Probability forecasts for the Seasonal (June to September) rainfall over the country as a whole based on the SEFS forecast.

7.2.2 Multi Model Ensemble (MME) Forecasting System Used for the Other Operational Forecasts

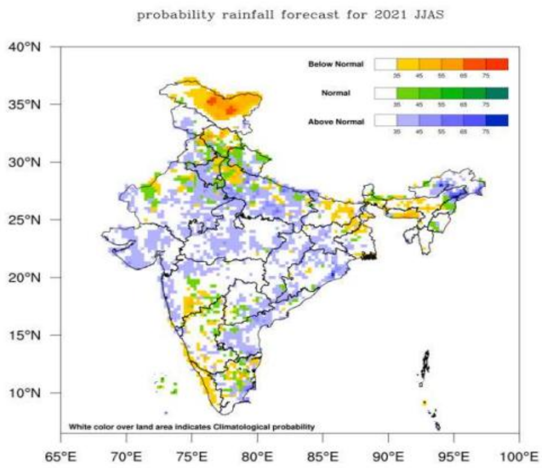
For generating April MME forecast for 2021 southwest Monsoon season rainfall, March initial conditions have been used. Climate models with the highest forecast skills over the Indian monsoon region including MMCFS have been used to generate MME forecasts. The MME forecast also suggests that the monsoon rainfall during the 2021 monsoon season (June to September) averaged over the country as a whole is likely to be normal (96-104% of LPA). The spatial distribution of probabilistic forecasts for tercile categories (above normal, normal and below normal) for the seasonal rainfall (June to September) is shown in Fig.7.4a.The spatial distribution suggests either normal or above normal probability is likely over most parts of the country.

The updated MME forecast for 2021 southwest Monsoon season rainfall has been computed using various coupled global model forecasts with May initial conditions. Climate models with the highest forecast skills over the Indian monsoon region including MMCFS have been used to prepare the MME forecast. The updated MME forecast also suggests that the monsoon rainfall during the 2021 monsoon season (June to September) averaged over the country as a whole is likely to be normal (96-104% of LPA). The spatial distribution of probabilistic forecasts for tercile categories (above normal, normal and below normal) for the seasonal rainfall (June to September) is shown in Fig.14.4b. The spatial distribution suggests normal or above normal seasonal rainfall is most likely over many areas of north west India, central India and eastern parts of the southern Peninsula. Below normal seasonal rainfall is most likely over some areas of north, east and neighboring northeast parts of the country and western parts of the south peninsula. The white shaded areas within the land area represent climatological probabilities.

(7.4a)



(7.4b)



7.2.3 Operational Forecast Model for the Date of Monsoon Onset over Kerala

An indigenously developed statistical model (Pai and Rajeevan, 2009) was used for preparing the operational forecast of the onset of monsoon over Kerala. The model based on 6 predictors used the principal component regression (PCR) method for its construction. Independent forecasts were derived using the sliding fixed window period of length 22 years. The model for 2021 was trained using data for the period 1998-2020. The forecast for the date of monsoon onset over Kerala was predicted on 14th May 2021 indicate that monsoon will set in over Kerala on

31st May with a model error of ±4 days. Southwest Monsoon onset in over Kerala on 03rd June, against the normal date of 01st June. Fig.7.5 shows the performance of the forecast for the period 1997-2020. The RMSE of the model is about 4 days.

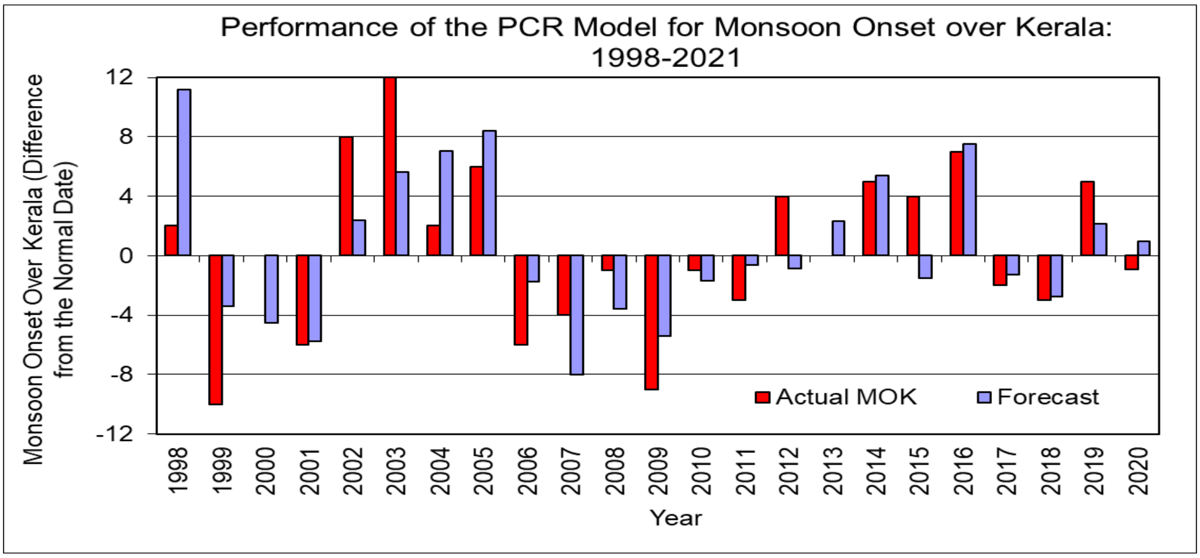


Fig.7.5: Actual dates of monsoon onset over Kerala and their predictions from the PCR model for the period 1998 - 2020.

7.2.4 Probabilistic Forecast Used for the Other Operational Forecasts

The tercile category forecasts for the four homogenous regions and MCZ for the 2021 southwest monsoon seasonal (June-September) rainfall based on the MME forecast generated using May initial conditions are given in the tables below.

Rainfall Category	NW India		Central India		South Peninsula	
	Range (% of LPA)	Forecast Probability (%)	Range (% of LPA)	Forecast Probability (%)	Range (% of LPA)	Forecast Probability (%)
Below Normal	<92	**27**	<94	**27**	<93	**33**
Normal	92-108	**41**	94-106	**34**	93-107	**34**
Above Normal	>108	**32**	>106	**39**	>107	**33**

Rainfall Category	Northeast India		Monsoon Core Zone (MCZ)	
	Range (% of LPA)	Forecast Probability (%)	Range (% of LPA)	Forecast Probability (%)
Below Normal	<95	**40**	<94	**27**
Normal	95-105	**33**	94-106	**33**
Above Normal	>105	**27**	>106	**40**

The MME forecast suggests that the monsoon rainfall averaged over the country as a whole during July 2021 is most likely to be normal (94 to 106 % of LPA). The spatial distribution suggests that below normal to normal rainfall probability is likely over many areas of northwest India and some parts of south peninsula, central, east and northeast India. Normal to above normal rainfall is most likely to experience over parts of central India and adjacent areas of peninsular India and Gangetic plains. The white shaded areas within the land area represent climatological probabilities

For the 2021 August rainfall averaged over the country as a whole is most likely to be normal (94 to 106 % of LPA). The LPA of the August rainfall over the country as a whole for the period 1961-2010 is 258.1 mm. The spatial distribution suggests that below normal to normal rainfall is likely over many areas of central India and some areas over northwest India. Normal to above normal rainfall is most likely over most parts of peninsular India and northeast India.

The 2021 August to September rainfall averaged over the country as a whole is most likely to be normal (95 to 105 % of LPA) with a tendency to be in the positive side of the normal. The LPA of the August to September period rainfall over the country as a whole for the period 1961-2010 is 428.3 mm. The spatial distribution suggests that below normal to normal rainfall is likely over many parts of the northwest, east and northeast parts of the country. Normal to above normal rainfall is most likely to experience over most parts of peninsular India and adjacent central India.

The rainfall averaged over the country as a whole during the September 2021 is most likely to be above normal (> 110 % of long period average (LPA)). The LPA of rainfall during September based on the data of 1961-2010 is about 170 mm. The forecast suggests that above normal to normal rainfall is likely over many areas of central India. Normal to below normal rainfall is most likely over many areas of northwest and northeast India and southern most parts of peninsular India.

The spatial distribution of probabilistic forecasts for tercile categories (above normal, normal and below normal) for the July, August, Aug-Sept & September rainfall are shown in Fig.7.6a, Fig.7.6b., Fig.7.6c. & Fig.7.6d. respectively. The white shaded areas within the land area represent climatological probabilities. The probabilities were derived using the MME forecast prepared from a group of coupled climate models. (* Tercile categories have equal climatological probabilities of 33.33% each)

Fig.7.6a: probability rainfall forecast for 2021 JUL

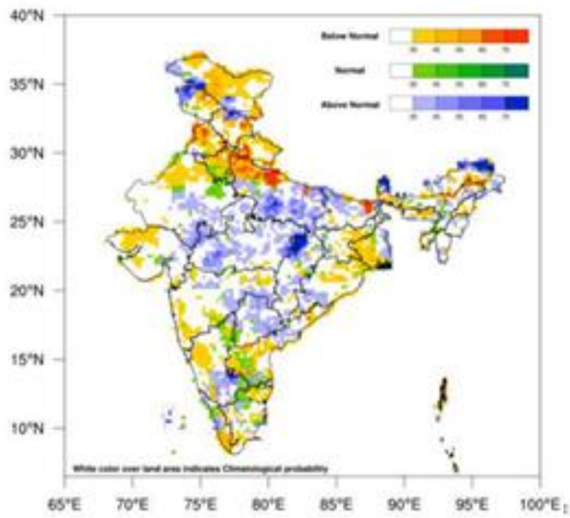


Fig.7.6b: probability rainfall forecast for 2021 AUG

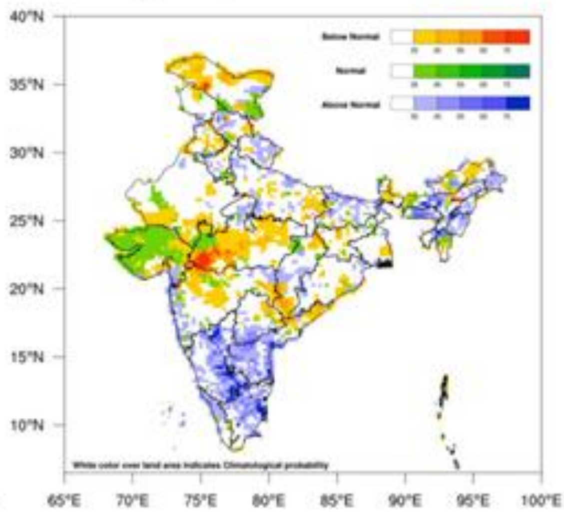


Fig.7.6c: probability rainfall forecast for 2021 Aug+Sep

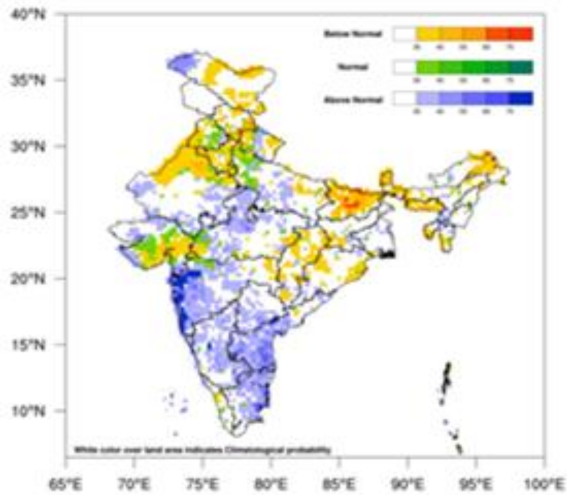


Fig.7.6d: probability rainfall forecast for 2021 SEP

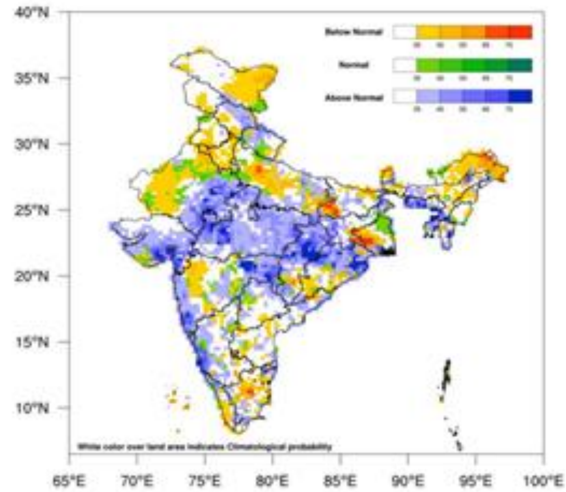


Fig.7.6a, Fig.7.6b., Fig.7.6c. & Fig.7.6d. are shown Probability forecast of tercile categories* (below normal, normal, and above normal) for the rainfall over India during July, August, Aug-Sept & September rainfall respectively.

7.3 Verification of Operational Forecasts

Based on an indigenously developed statistical model, monsoon onset forecast issued on 14th May 2021 indicate that monsoon will set in over Kerala on 31st May with a model error of ±4 days. The actual monsoon onset over Kerala was on 3rd June and therefore the forecast was correct and within the error limit.

Table-7.5 gives the summary of the various operational long range forecasts issued for the 2021 Southwest monsoon rainfall along with the realized rainfalls

The first stage forecast for the season (June-September) rainfall over the country as a whole issued in April was 98% of LPA with a model error of ± 5% of LPA. The update issued in June for this forecast was (101% of LPA) with a model error of ± 4% of LPA. The actual season rainfall for the country as a whole was 99% of LPA, which are within the April and June forecasts limit respectively. Thus, the both the forecasts were correct.

Considering the four broad geographical regions of India, the forecasts issued in 1st June for the season rainfall over Northwest India, Central India, Northeast India and South Peninsula were Normal (92-108% of LPA), Above Normal (>106% of LPA), Below Normal (<95% of LPA) & Normal (93-107% of LPA) respectively. The newly introduced seasonal rainfall over Monsoon Core Zone (MCZ) was forecast as Above Normal (>106% of LPA). The actual rainfall over Northwest India, Central India, Northeast India, South Peninsula and Monsoon Core Zone were 96%, 104%, 88%, 111% and 107 % of the LPA respectively. The monthly forecast issued for July, August & September were normal (94 to 106 % of Long Period Average (LPA)), normal (95 to 105 % of Long Period Average (LPA)) with a tendency to be in the positive side of the normal & above normal (> 110 % of Long Period Average (LPA)) respectively. The actual rainfall for the country as a whole for July was 93% fo LPA, August was 76% of LPA whereas for September was 135%of LPA. The forecast for the second half of the monsoon season (August – September) for the country as a whole was normal (94 to 106 % of Long Period Average (LPA)) whereas actual rainfall was 99% of LPA.

Table-7.5: Performance of the operational forecast issued for the 2021 southwest monsoon rainfall.

Region	**Period**	**Forecast (% of LPA)**	**Actual Rainfall**
			(% of LPA)
		(issued on 16th April)	
All India	**June to September**	**Normal (96-104% of LPA) 98± 5 of LPA**	**99**
		(issued on 1st June)	
All India	**June to September**	**Normal (96-104% of LPA)**	**99**

		101± 4 of LPA	
Northwest India	June to September	Normal (92-108% of LPA)	96
Central India	June to September	Above Normal (>106% of LPA)	104
Northeast India	June to September	Below Normal (<95% of LPA)	88
South Peninsula	June to September	Normal (93-107% of LPA)	111
Monsoon Core Zone	June to September	Above Normal (>106% of LPA)	107
All India	June (1st June)	Normal (92 to 108% of LPA)	109
All India	July (issued on 1st July)	July: Normal (94-106% of LPA	93
All India	August & Aug-Sept (issued on 2nd Aug)	August: Normal (94-106% of LPA	76
		Aug+Sept: Normal (95-105% of LPA)	99
All India	September (issued on 1st Sept)	Above Normal (>110% of LPA)	135

7.4 Dynamical Seasonal Forecasting System

7.4.1 Monsoon Mission Coupled Forecast System (MMCFS)

The National Monsoon Mission (NMM) project was launched by the MoES in 2012 for developing a state-of-the-art dynamical prediction system for monsoon rainfall on different time scales. Climate Forecast System version 2 (CFSv2) of National Centers for Environmental Prediction (NCEP), USA was identified as the basic modeling framework for this purpose. The latest version of the high resolution (horizontal resolution of approximately 38km (T382)) MMCFS for the seasonal forecasting of monsoon rainfall was recently implemented at the Climate Research and Services, IMD, Pune and it has been used to generate the experimental forecast for 2017 southwest monsoon rainfall. This is a worthwhile improvement over the original version which had a resolution of about 100 km.

The model climatology was prepared using retrospective forecasts generated for 27 years (1982-2008). The retrospective forecasts were prepared based on average of ten (10) ensemble members. The skill scores of the MMCFS model for the forecasting of seasonal rainfall over the country as a whole with different Initial conditions are given in the Table-7.6. The performance of the model for the period 1982-2008 is given in the Fig.7.5. The seasonal forecasts from CFS for the 2021 southwest monsoon rainfall over the country as a whole are also given in the table. The spatial pattern of the forecast for 2021 JJAS rainfall anomaly based on April initial conditions is given in the Fig.7.6. The updated forecast issued for JJAS generated with May initial conditions consisting of 50 ensemble members. Spatial pattern of the forecasted rainfall anomaly based on May initial conditions is given in the Fig.7.7.

Based on the above modelling framework, seasonal forecasts were prepared by using various initial conditions. The model hindcasts and forecasts were bias corrected using the z-score transformation (correction for both mean and variance) method (The long period average (LPA) was calculated based on the 1961-2010 normal). As seen in the Table-7.6, the forecast based on March conditions was 25% more than LPA whereas the actual JJAS rainfall was 99% of LPA. The updated forecast based on May conditions was 11% of LPA more than normal rainfall. This suggests that the model forecast for the 2021 southwest monsoon season over the country as a whole was overestimated and was not within forecast limits and correct.

Table-7.6: The skill scores of the Monsoon Mission CFS model for the forecasting of seasonal rainfall over the country as a whole at two different initial conditions March and May respectively. The forecast for the 2021 season rainfall over the country as a whole is given in the last column.

Initial conditions (IC) of	JJAS		Forecast for 2021 (% of LPMA)
	C.C (1982-2008)	RMSE (%of LPMA) (1982-2008)	
March	0.47	8.60	125
May	0.23	8.66	111

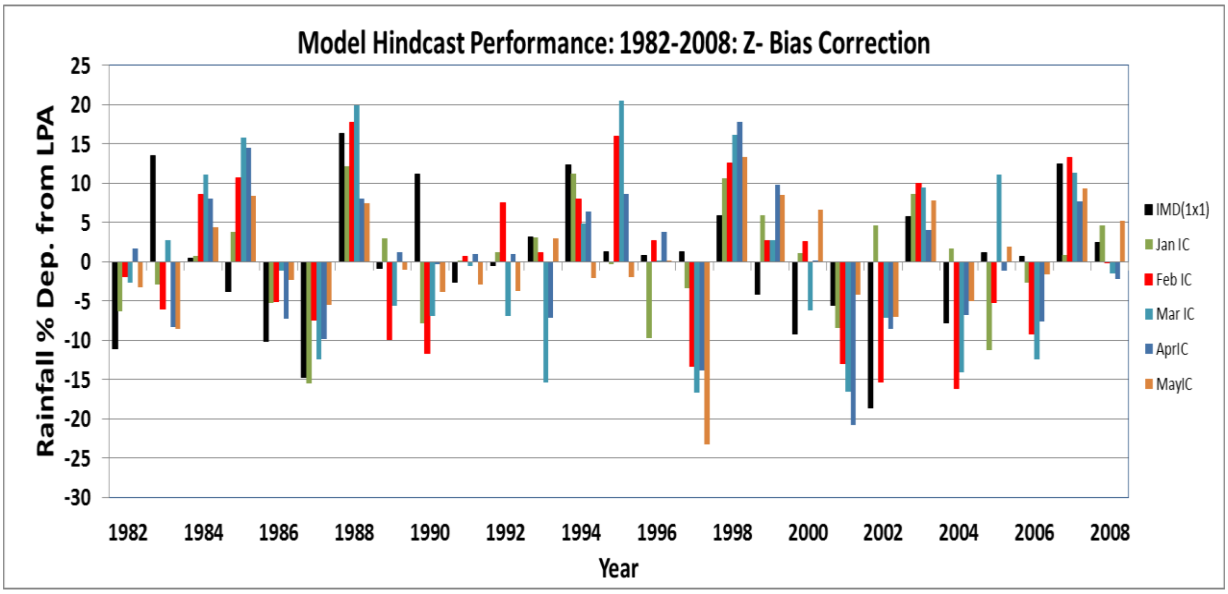


Fig.7.5. Performance of the model hindcast for the southwest monsoon season (June-Septeber) rainfall over the country as a whole based on various initial conditions. The model hindcasts were bias corrected using the z-score transformation (correction for both mean and variance) method.

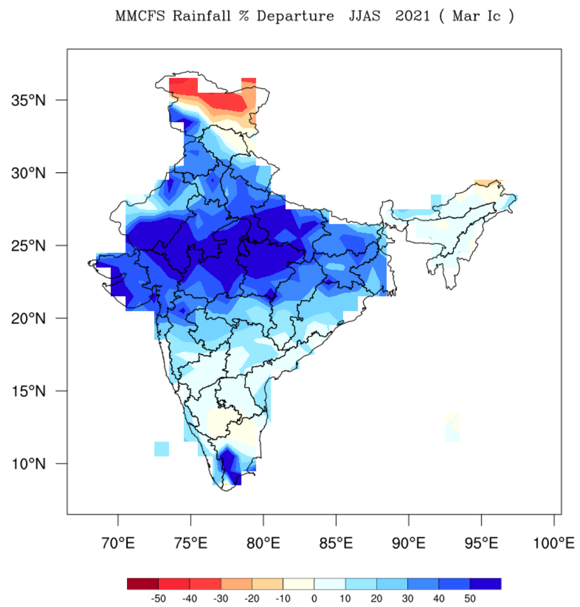


Fig.7.6. Rainfall anomaly forecast over Indian region for the 2021 monsoon season computed from the MM CFS model based on March IC.

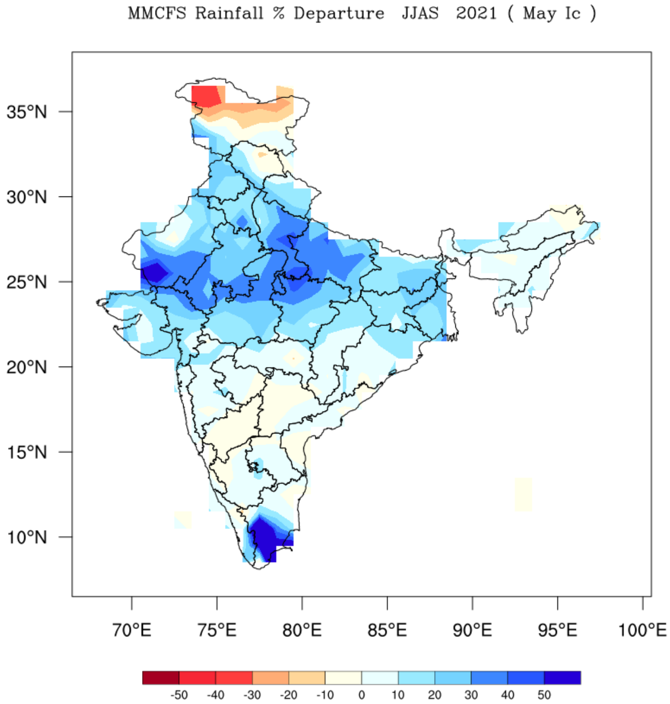


Fig.7.7. Rainfall anomaly forecast over Indian region for the 2021 monsoon season computed from the MM CFS model based on May IC.

7.4.2 Forecasts for Seasonal Rainfall from other Indian Institutes

Inferences derived from forecasts from various centers for the 3 months periods of JJA and JAS are given in Table-7.7. Forecast consists of individual coupled model forecast as well as Multi-Model forecasts based on forecasts from atmospheric as well as coupled atmospheric-ocean models. The forecasts were issued in May 2021. Coupled model forecast for southwest monsoon 2021 from most of the centers indicating normal to above normal rainfall over the most parts of the country except some of the east and northeastern parts of the country. However, there are differences in the spatial patterns of the various rainfall anomaly forecasts.

Table-7.7: Forecasts for 2021 southwest monsoon season rainfall over the country as a whole received from various climate research centers/ research groups/ individuals.

S.No.	Institute/Source	Model	April Forecast (% of LPA)	Updated Forecast
1	Dr. M. S. Narayanan (SRM University)	Deep Learning Technique	103% of LPA (+ / -) 6% (Normal)	NO Update

2	NCMRWF	Coupled Model (Regional)	normal to above normal	NO Update
3	Dr. Kishtawal , SAC, ISRO	Genetic Algorithm	942 mm, 105.8% of LPA (+ / -) with error 28mm (3% (Normal))	NO Update

7.4.3 Forecasts from Major International Climate Prediction Centers

Several international climate prediction centers regularly generate and provide global seasonal forecasts based on dynamical models (Atmospheric/ coupled GCMs) through web. Some of these centers also prepare Multi-Model Ensemble (MME) forecasts using combinations of forecasts prepared by different centers. It may be mentioned that none of these centers prepare forecasts specifically for the Indian region. The skill of the multi model ensemble forecasts has been found to be better than that of the individual models. Inferences derived from the MME forecasts for JJA/JAS rainfall from 5 centers and individual coupled model forecasts from 4 centers issued in April/ May are summarized in the Table-7.8. It is seen from the Table-7.8 that the forecasts from most of the models were indicating above normal to normal rainfall over the country as a whole during the 2021 southwest monsoon season. However, there are differences in the spatial patterns of the various rainfall probability & anomaly forecasts.

Table-7.8: Inferences derived from seasonal forecasts from various climate centers for the 2021 southwest monsoon season issued during April/May 2021.

S. No	Centre issuing the Forecast	Method	Inference for 2021
1.	ECMWF, UK	Coupled Model	JJA (Issued: May 2021): Enhanced probability for above normal rainfall is most likely over most parts of northern India and neighboring region, some parts from North East India. Probability for normal rainfall is most likely over remaining parts of the country. JAS (Issued: May 2021): Enhanced probability for above normal rainfall is most likely over most parts of North West India & neighboring region, some parts from North East India Central India and south eastern parts of south peninsula. Probability for normal rainfall is most likely over remaining parts of the country.

2.	International Research Institute for Climate and Society, USA	MME 7 Models (AGCM & CGCM)	JJA & JAS (Issued: May 2021): Enhanced probability for above normal rainfall is most likely over most parts of northern India and neighboring region & eastern parts of central India. Enhanced probability for below normal rainfall is most likely over parts of south western coast and some parts of North East India. Climatological probability is likely over the remaining parts of the country.
3.	APEC Climate Center	MME 6 Models (AGCM & CGCM)	JJA & SON (Issued: May 2021): Enhanced probability for above normal rainfall is likely over the parts of northern, western, central and adjoining south peninsular India & some of the eastern parts of India. Enhanced probability for below normal rainfall is most likely over parts of south western coast. Climatological probabilities for remaining parts of the Country.
4.	WMO LRFMME	MME of 4 coupled models	JJAS (Issued: May 2021): Enhanced probability for above normal rainfall is most likely over parts of extreme North India, few parts of western India, parts from North East India and adjoining areas. Enhanced probability for below normal rainfall is most likely over small region from south west coast of India. Climatological probability over the remaining parts of the country.
5.	Met Office, UK	Coupled Model	JJA (Issued: May 2021): Enhanced probability for above normal rainfall over some parts from central, southern, northern and north east India. Enhanced probability for below normal rainfall is most likely over parts of western India and south eastern parts of south peninsula.
6.	NMME, NCEP	MME of 8 Models & coupled models	JJA & JAS (Issued: May 2021): Enhanced probability for above normal precipitation is likely over parts of West, Central and adjoining north India and south peninsular India. Enhanced probability for below normal precipitation is likely over fewer parts of east and north east India. Probability for normal precipitation is likely over rest of the country.
7.	COPERNICUS	MME of 6 Models & coupled models	JJA (Issued: May 2021): Enhanced probability for above normal rainfall is likely over West, Central and adjoining north India and south peninsular India. Probability for normal rainfall is most likely over the remaining parts of the country.
8.	NCEP CFSSv2	Coupled Model	JJA & JAS (Issued: May 2021): Positive rainfall anomalies are predicted over parts of southeast coastal region of India. Negative rainfall anomalies are predicted over parts of southwest coastal region of India. Normal rainfall anomalies are predicted over the remaining parts of the country.

7.5 Conclusions

Based on an indigenously developed statistical model, it was predicted on 14th May 2021 that monsoon will set in over Kerala on 31st May with a model error of ±4 days. However, the actual monsoon onset over Kerala took place 3rd June within the limit of model error of ±4 days and therefore the forecast was correct.

IMD has adopted a new strategy for issuing monthly and seasonal operational forecasts for the southwest monsoon rainfall over the country by modifying the existing two stage forecasting strategy. The new strategy is based on the existing statistical forecasting system and the newly developed Multi-Model Ensemble (MME) based forecasting system. The first stage long range forecast issued on 16th April consisted of only forecast for season (June-September) rainfall over the country as a whole. In the second stage (1st June), along with the update for the April forecast, forecast for season rainfall over the four broad geographical regions (northwest India, Central India, South Peninsula and northeast India) and that for monthly rainfall over the country as a whole for the months of July, August, September & Aug-Sept were issued. In addition to that, IMD has also issued a separate forecast for the Monsoon Core Zone (MCZ),

The first stage forecast for the season (June-September) rainfall over the country as a whole issued in April was 98% of LPA with a model error of ± 5% of LPA. The update issued in May for this forecast was (101% of LPA) with a model error of ± 4% of LPA. The actual season rainfall for the country as a whole was 99% of LPA, which is within the forecast limits of the April and May forecasts. Thus the both the forecasts were within the forecast limits.

Considering the four broad geographical regions of India, the forecasts issued in 1st June for the season rainfall over Northwest India, Central India, Northeast India and South Peninsula were Normal (92-108% of LPA), Above Normal (>106% of LPA) , Below Normal (106% of LPA). The actual rainfall over Northwest India, Central India, Northeast India, South Peninsula and Monsoon Core Zone were 96%, 104%, 88%, 111% and 107 % of the LPA respectively. The monthly forecast issued for July and August were overestimated whereas for September was within the range of the forecast. The forecast for the second half of the monsoon season (August – September) for the country as a whole was within the forecast limit.

While issuing the long range forecast in the month of April, ENSO Neutral conditions where prevailed over Pacific Ocean. La Niña conditions (colder than normal SST over the equatorial Pacific) were developed during second part of the 2020, which peaked in November. However, La Nina conditions over the equatorial Pacific started weakening in the early part of 2021. IMD's analysis of continuation of ENSO neutral conditions in the early part of the 2021 monsoon season based on MMCFS and other global model forecast indicate further warming trends came correct. IMD's analysis also indicated correctly the weakening of Neutral IOD episode prevailing prior to monsoon season and the emergence of negative Indian Ocean Dipole (IOD) in the middle of the monsoon season.

Monthly forecast issued for June 2021 likely to be normal (92-108% LPA) and the June rainfall was above normal (109% of LPA). The monsoon onset of monsoon over Kerala (3rd June), the monthly rainfalls during the July and august months were below the LPA and above normal in September 2022. It may be noted that IMD forecast for monsoon onset over Kerala (31st May with model error of ±4 days) was correct. ENSO neutral conditions over equatorial Pacific and Neutral IOD conditions over Indian Ocean were prevailed in the beginning of Monsoon season. Further cooing of equatorial Pacific SSTs and developed La Nina conditions in the end of monsoon season. IMD forecast correctly indicated the development of the negative IOD conditions during monsoon season. Rainfall activity decreased significantly in the month of August mainly due to the impact of negative IOD conditions over the Indian Ocean. Monthly forecast issued for July and August 2021 likely to be normal (94-106% LPA), however the observed rainfall was 93 and 76% of LPA respectively. Increase the rainfall activity in week of August, momentum of good rainfall activity continued up to end of the monsoon season. IMD forecast correctly indicated the above normal (>110% LPA) rainfall likely during September month and observed rainfall was 135% of LPA. The more rainfall during the September mainly due to the longer life of a series of low-pressure systems formed over the region and few systems intensified in to depression and tropical cyclone category. Most of the systems moved along the monsoon trough resulting in above normal season rainfalls over Central India and below normal season rainfall over North-East India. Season rainfall over North-East India was below normal and IMD forecast indicated below normal rainfall over the region in the seasonal forecast. Thus, IMD's forecast for geographical rainfall distribution of highest rainfall over central India and lower rainfall over North-East India also came correct though the received rainfall over South

Peninsula was more than the upper forecast limits. Overall, the impact of synoptic scales systems on the monsoon performance was very significant this year.

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8

STUDY OF MONSOON FEATURES USING SATELLITE PRODUCTS

Chinmay Khadke and S C Bhan

8.1: Introduction

The vast expanse of the region covered by Indian summer monsoon circulation makes it necessary to have a large scale synoptic view of the weather. Geostationary satellites allow such large scale simultaneous observations. Their wide spatial coverage along with near real-time data availability makes it an indispensable tool at the hands of meteorologists. India Meteorological Department has employed two dedicated geostationary meteorological satellites for observations centredover the Indian region. These are multi-spectral satellites with 30 minutes of temporal resolution each. There are two payloads each, one is a 6 channels imager giving 2-D observations and another is 19 channels sounder allowing detection of vertical temperature and humidity profiles; and other derived products. These satellites provide a combined temporal frequency of 15 minutes as they are used in staggered mode. Table 8.1 shows the details of the frequencies of the Imager payload.

Channel number	Name	Spectral wavelength	Spatial Resolution
1	Visible (VIS)	0.65 µm	1 km
2	Short-wave Infra-red (SWIR)	1.62 µm	1 km
3	Mid Infra-red (MIR)	3.90 µm	4 km
4	Thermal Infra-red 1 (TIR1)	10.80 µm	4 km
5	Thermal Infra-red 2 (TIR2)	12.00 µm	4 km
6	Water Vapour (WV)	6.80 µm	8 km

Table 8.1: INSAT 3D and 3DR Imager channels

8.2 : Data and Methodology

Based on the remotely sensed multi-spectral information from the satellites, various imagery and products are generated. The imagery from various spectral channels gives different information depending on the spectral wavelength and the physical properties of the target object. Hence the imagery of each channel/spectral wavelength plays a specific role in the monitoring of weather. The information from these multiple wavelengths can be combined to generate RGB images. These RGB images allow us to have multi-spectral information in a single image thereby reducing the analysis time and better interpretation. Specific dynamical/meteorological parameters can be derived by combining Information sensed by various channels and numerical weather model fields. These derived parameters are atmospheric motion vectors, rainfall, Outgoing longwave radiation etc.

The present study uses multispectral imagery, RGB images and derived products from INSAT 3D, INSAT 3DR, METEOSAT-8as well as multiple polar-orbiting satellites to monitor and study different monsoon features.

8.2: Monsoon features monitored using satellites

8.2.1: The onset of monsoon over Kerala

The onset of monsoon is an important feature and its monitoring is dependent on the satellite observations. The convection and the depth of wind field over an oceanic region off coast Kerala form two of the three criteria monitored specifically for the onset of monsoon.

One of the criteria used to monitor the onset of monsoon over Kerala is the daily Outgoing Longwave Radiation (OLR) values over an Oceanic area bounded by Lat. 5- 10°N and Long. 70°-75°E. Higher convection over the region limits the outgoing Longwave radiation reaching the satellite. Thus lower OLR values indicate the presence of intense convection in the region. OLR vales in this bounded area should be less than 200 wm^{-2} at the time of onset. The daily OLR product is formed by binning the 48 half-hourly OLR images of the day. These values are monitored from 15^{th} May onwards. The graph of daily OLR values over the prescribed region for May-June 2021 is shown in Fig.8.1. As observed in the graph the daily average OLR values over the prescribed region in the last week before the onset date of 3^{rd} June are over the threshold of 200 wm^{-2}. The reduction in the OLR values during the 22^{nd} to 26^{th} was caused by the formation of tropical cyclone Tauktae in the southeast Arabian sea.

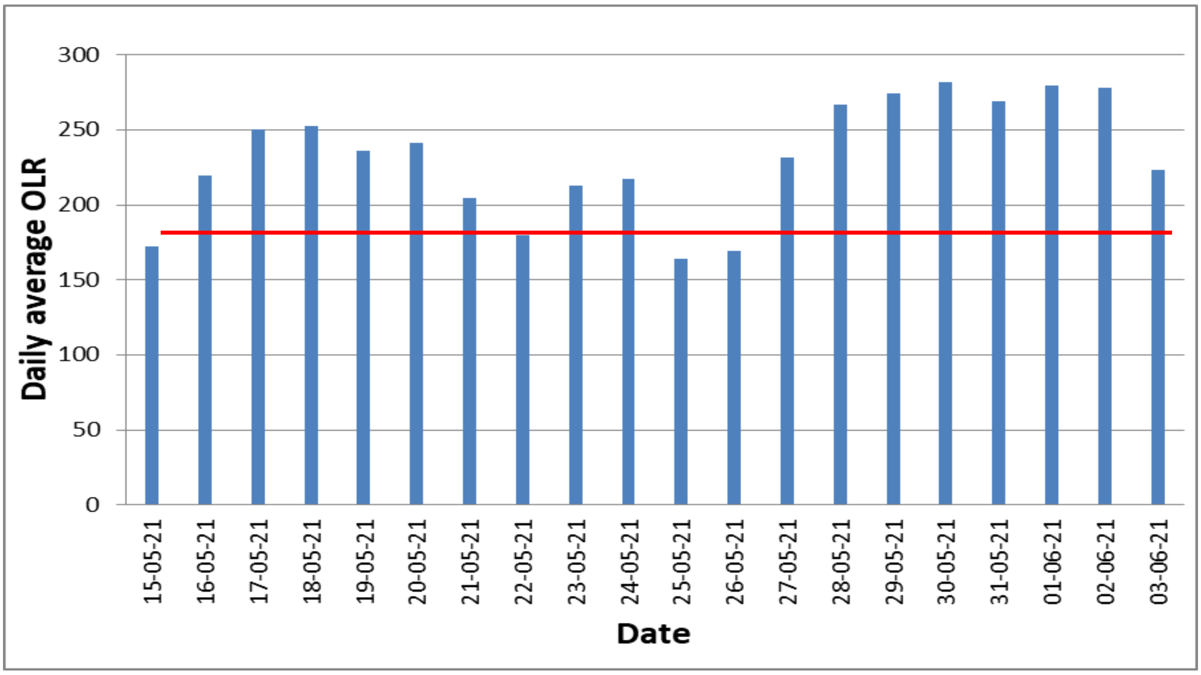

Fig.8.1: Daily average OLR over the onset phase

Other such criteria are the depth and strength of westerly winds over a specified region. The region monitored for the depth of westerly winds is the area between the equator to Lat. 10°N and Long. 55°E-80°E and that for the strength of zonal wind speed is the area bounded by Lat. 5°-10°N, Long. 70°-80°E. Depth of westerly winds should be upto 600 hPa and the magnitude of winds should be of the order of 15-20 kts upto 950 hPa. Visible, MIR and IR1 channels are used to derive atmospheric motion vectors which are used in the monitoring of the winds at different levels. Satellite-based winds of 1st June 2021 shows wind speeds of 15 to 20 kts over the region marked in red. On the date of onset i.e. 3rd June, the westerly winds of 20ktsare seen upto a depth of 600hPa indicating the increased strength and depth of the westerly field.

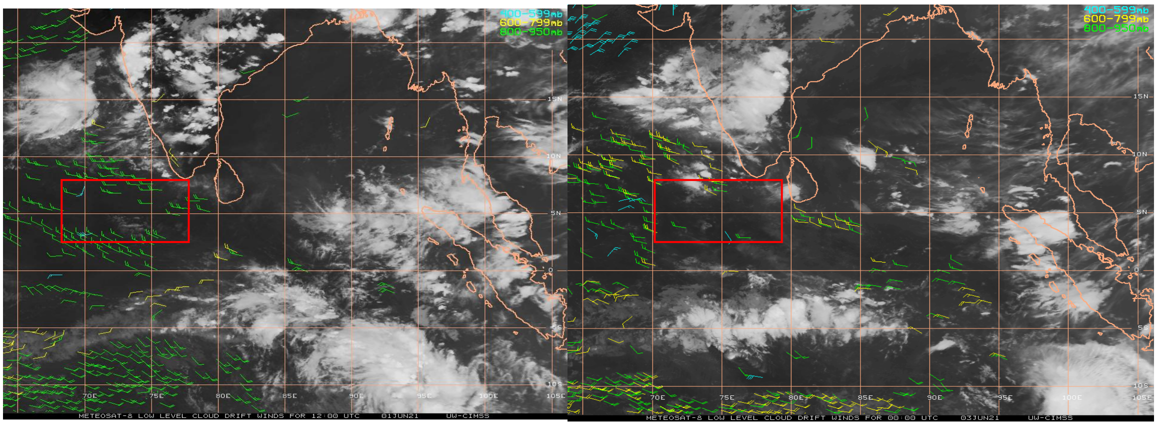

Fig.8. 2: Low-Mid Level Satellite derived winds, prescribed area marked with the red box

8.2.2: Low-pressure systems

Monsoon ischaracterized by the genesis of multiple low-pressure systems over the entire monsoon season. Low-pressure systems such as Cyclones and depression forming at different life stages affect the performance of the monsoon, its onset as well as withdrawal. As these systems are generated over the data-sparse oceans, their monitoring is mostly dependent on the satellites. These systems cause copious rainfall over the region they traverse. Thusmonitoring of such systems throughout their life-cycle thus becomes very important. Polar-orbiting satellites along with geostationary satellites are used to monitor such systems. Passive and active microwave remote sensing based on polar-orbiting satellites gives us more information about the associated convection and the sea surface wind speeds that allows us to monitor the strength of the systems.

The monsoon season of 2021 was characterized by two cyclones each at the onset and the withdrawal period. “TAUKTAE”, over the Arabian Sea (14th to 19thMay) and severe Cyclonic storm “YAAS” over Bay of Bengal (23rdto 28thMay) formed during the onset phase of monsoon. Advanced scatterometer (ASCAT) payload on METOP series of satellites is an active type of sensor which uses the property of asymmetric scattering of directed energy by sea surface to derive the winds at Sea surface. Fig.8.3(a) shows one such pass of ASCAT over TC Tauktae on 15thof May indicating strong winds over the east-central Arabian Sea and adjoining Lakshadweep sea. This cyclone moved along the western coast of India and caused a good amount of rainfall over all the western coastal states. Another such ASCAT pass shown in Fig.8.3(b) shows surface wind structure over the Bay of Bengal on 24thof May caused by the presence of TC Yass. The formation and movement of the cyclone helped increase cross-equatorial flow during the onset phase of the monsoon.

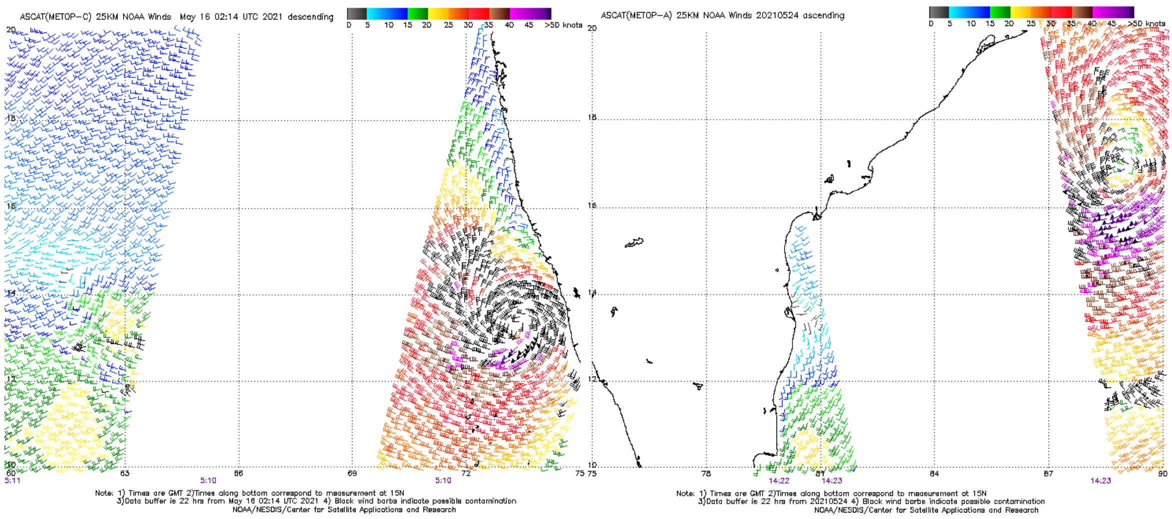

Fig.8.3: ASCAT winds for (a)Tauktae (left) and(b)Yass (right)

The withdrawal period also witnessed the formation of a monsoon depression and a cyclonic storm “GULAB” in the month of September. Microwave payloads over the polar-orbiting satellites allow better detection of convection through clouds. Fig.8.4(b) depicts the convective structure of TC Yass over the BoB. This system made landfall over the eastern coast, weakned over the southern peninsular region but continued its west-northwesterly movement. The remnant of this system crossed the peninsula and again intensified over the Arabian sea forming TC Shaheen. These systems caused large amounts of rainfall as shown in Fig. 8.4(a) the weekly satellite-derived rainfall product. These rainfall estimates prove very useful in assessing the rainfall features not only over oceans but remote regions in real-time. These systems had an unfavourable impact on the monsoon withdrawal and it extended the withdrawal of monsoon further into the month of October.

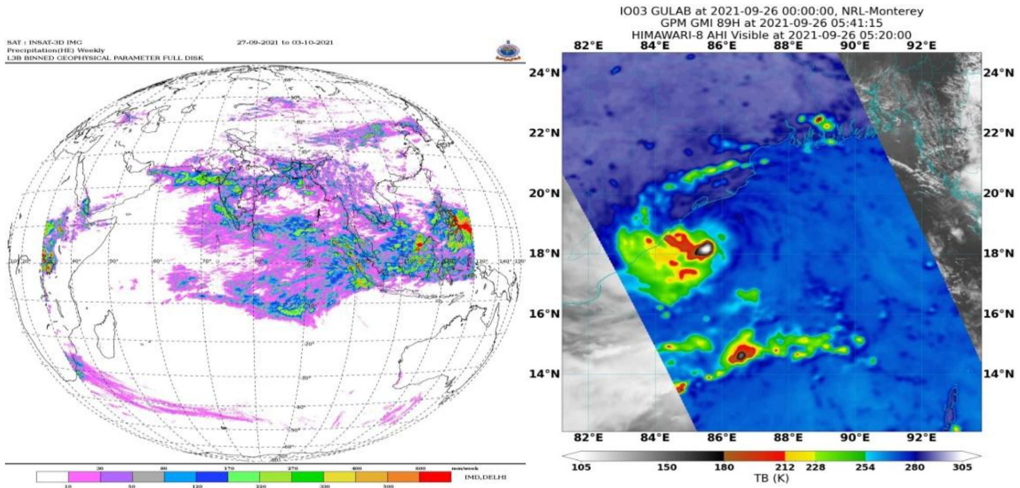

Fig. 8.4 (a) Rainfall caused by Gulab (left) and (b)Convective structure of TC Gulab .

8.2.3: Monsoon withdrawal

The withdrawal of monsoon is monitored from 1st September onwards. It depends on the establishment of an anticyclone, cessation of rainfall activity and reduction in moisture content as observed in Satellite WV imagery. Withdrawal begins from the northwest region and it withdraws from the entire country normally by 15thOctober. The withdrawal is declared keeping in the spatial continuity, reduction in moisture as usually depicted in the water vapour imageries and prevalence of dry weather for 5 days. Using the water vapour channel in the satellite, the moisture content in the middle levels of the atmosphere can be detected. This imagery then helps decide the withdrawal of monsoon from the particular region.

This year the withdrawal of monsoon was delayed due to the formation of Tropical cyclones as discussed in the earlier section. These systems slowed down the wind regime changes. The water vapour channel present in the imager is sensitive to the mid-upper tropospheric atmosphere. The moisture detected by this channel is tracked over time to derive the water vapour winds. Fig.8.5(a) shows the high-level satellite-derived winds on the 21stof October. This shows the presence of anti-cycer and the absence of water vapour over the northwest region, the features conducive to the withdrawal. Owing to these features and the reduction of rainfall over the large region [Fig. 8. 5(b)], the withdrawal of the southwest monsoon up to the central parts of the country was declared on 22nd October. Consequentely, with further reduction in rainfall over most of the parts of the country and setting in of northeasterly winds in the lower tropospheric levels, complete withdrawal of southwest monsoon was declared on 28th October.

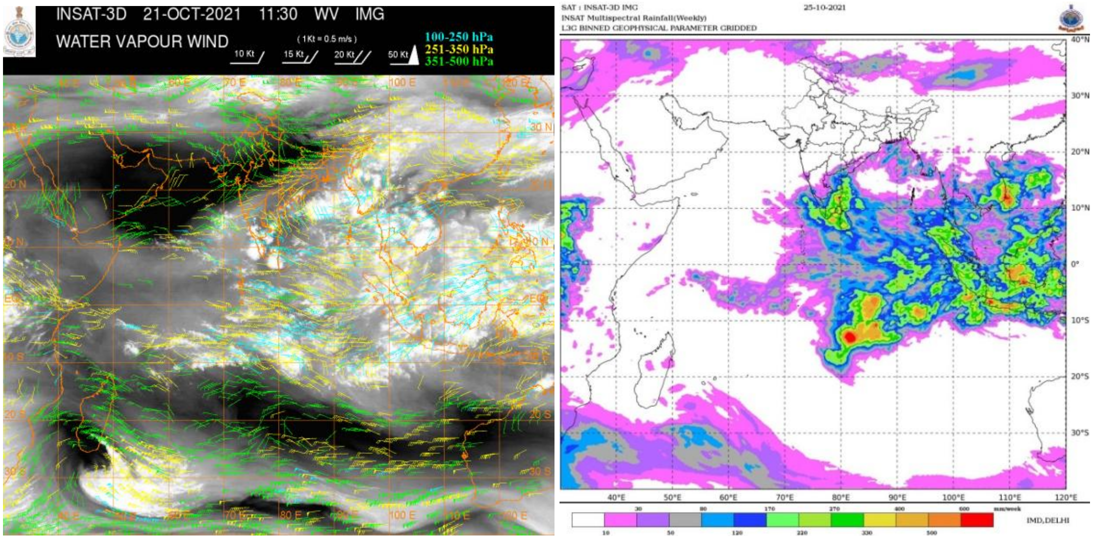

Fig.8.5(a) Water vapour based high-level winds(left) and (b) satellite-based weekly rainfall estimates ending on 25th October.

8.2.4 : Conclusion

Satellite based remote sensing is a vital observation system at the disposal of meteorologists. The large scale observational capability along with near real-time data availability allows for the operational monitoring of weather parameters. The derived products such as Atmospheric motion vectors and rainfall estimates make it even more informative for the forecasters.

Acknowledgement

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9

AGROMETEOROLOGICAL FEATURES OF THE MONSOON AND SERVICES PROVIDED DURING SOUTHWEST MONSOON 2021

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9.1 : Introduction

As a large part of the country depends on monsoon rainfall for agricultural activities, the onset, advance and subsequent distribution of rainfall during the monsoon season areextremely important for *kharif* crop production. Advance information on these monsoon features further aids in crop planning for the season. During the year 2021, the southwest monsoon has set in over Kerala on 3rd June 2021, which was two days later than its normal onset date. Thereafter its progress was normal till 19th June when it covered major parts of the country except some parts of Northwest India, i.e. western parts of Uttar Pradesh, Delhi, Punjab, Haryana and Rajasthan. Subsequently, the monsoon became active again on 12th July and covered the entire country on 13th July against its normal date of 08th July (Fig. 9.1). Keeping pace with the onset and advancement of Monsoon, sowing/transplanting of *kharif* crops started in Kerala and the north-eastern states of the country as per the normal sowing window. However, due to delay in advancement of Monsoon in some parts of the country, sowing could be undertaken after mid July.

The total rainfall during the southwest monsoon season i.e. 1st June to 30th September 2021 has been normal i.e. 870 mm against the long period average (LPA) of 880 mm (99% of its LPA) for the country as a whole. The rainfall distribution in June was above normal (110%), whereas, in July, the country received slightly below normal rainfall (93%). During August, several unfavourable features for monsoon, such as negative Indian Ocean Dipole prevailed during the month, absence of formation of monsoon depression and a smaller number of low-pressure areas over the Bay of Bengal, resulted in the deficient rainfall for the country (76%). Excess rainfall (135%) was witnessed in September, which was mainly associated with the formation of deep depression during 12th – 15th September and cyclonic storm “GULAB” over Bay of Bengal during 24th-28th September.

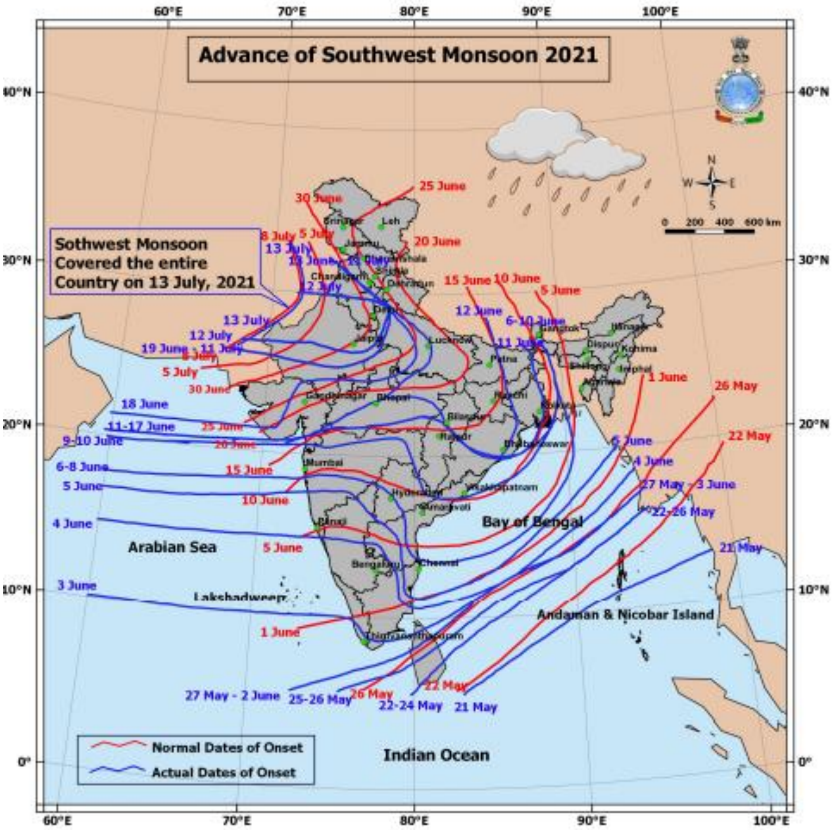

Fig. 9.1: Advancement of Southwest Monsoon 2021.

Although the total rainfall duringmonsoon 2021 was normal for the country as a whole, large fluctuations have been observed in its distribution over spatial and temporal scales. A major portion of the country including Maharashtra, Gujarat, Goa, Madhya Pradesh, Chhattisgarh and Odisha experienced a deficiency in rainfall till August. However, the excess rains during September helped to ensure a normal monsoon(Fig.9.2). Six Meteorological subdivisions *viz.*, Nagaland, Manipur, Mizoram & Tripura, Assam and Meghalaya, Arunachal Pradesh, Jammu & Kashmir and Ladakh, West Uttar Pradesh and Lakshadweep,that occupy 17% of the total area of the country, received deficient rainfall during the season.

Due to variability in spatial and temporal distribution of rainfall, Meteorological subdivisions like Gangetic West Bengal, Coastal Andhra Pradesh, Telangana, Vidarbha, Marathwada and Gujarat region (South Gujarat) experienced floods, while Saurashtra & Kutch, Gujarat region (Northern parts) and West Rajasthan experienced prolonged dry spells during the season. Different districts of Odisha witnessed both the extreme events, i.e. floods and droughts during various periods of the season. This extreme variability in rainfall affected the overall growth of major crops over these regions.

Various Agromet products like Standardised Precipitation Index (SPI), Normalised Difference Vegetation Index (NDVI) (Fig.9.4and Fig.9.7), Vegetation Condition Index (VCI), Temperature Condition Index (TCI), the spatial distribution of weather parameters etc., have been used to monitor crop condition across the country to generate appropriate AgrometAdvisories during the crop growing season.

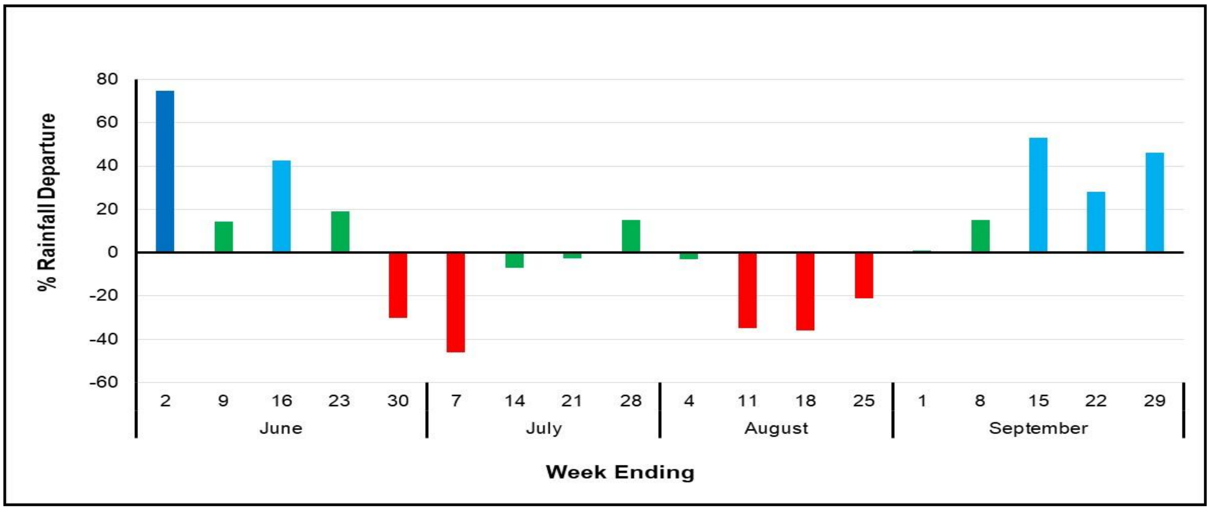

Fig. 9.2:Week-by-week rainfall departure (%) from LPA for the country as a whole.

9.2 : Major weather systems that affected the country during southwest Monsoon 2021

A) Impacts on crops and Agromet Advisory Services (AAS) under various rainfall situations

a. Dry spells/ deficient rainfall and related Agromet advisories

Sowing of Crops

Sowing/transplanting of *kharif* crops started in Kerala, north-eastern states and many parts of the country as per the normal sowing window due to normal onset and advancement of monsoon upto third week of June. However, due to delay in advancement of Monsoon and/or subdued rainfall activity during later part of June and first fortnight of July, in some parts of the country, *viz.*North Interior Karnataka, Western Jharkhand, Northern Madhya Pradesh, North Gujarat, Delhi and Haryana, Saurashtra and Kutch regions andRajasthan, farmers could undertake sowing after mid July. During the period, farmers were suggested to undertake sowing of suitable vrieties of–

- guar and pearl millet in Haryana,
- maize in Delhi,
- pearl millet, sorghum, maize, sesame and cluster bean in Rajasthan,
- groundnut, sesame, green gram, black gram, pearl millet, cowpea and cotton inSaurashtra and Kutch and North Gujarat,
- soybean, arhar, sesamum and maize in Northern parts of Madhya Pradesh,
- green gram, black gram, red gram, groundnut, soybean, cotton, maize, sorghum, sunflower, bajra and sesamum crops in North Interior Karnataka and
- pigeon pea, black gram, sorghum, finger millet and soybean in Western Jharkhand.

Districts having impacts on crops due to deficient rain in various States during southwest Monsoon 2021 have been presented in Fig. 9.3.

Maharashtra

Sowing of regular *kharif* crops,like *kharif* sorghum, groundnut, cotton, green gram and black gram,could not be undertakenwithin normal sowing window in Nandurbar andDhuledistricts of Maharashtra due to receipt of insufficient rains during June and the first fortnight of July 2021. Accordingly, farmers were advised to undertake sowing of contingent crops only after the receipt of adequate rainfall (80 to 100 mm) resulting in sufficient soil moisture under *vapsa* conditions. The contingent crops, as suggested to the farmers for sowing, are–

- pearl millet, sunflower, tur, castor, horse gram etc. and intercropping of sunflower + tur (2:1) and pearl millet + tur (2: 1) cropsinNandurbardistrict and
- soybean, cotton, hybrid sorghum, hybrid bajra, pigeon pea, sunflower, sesamum, maize and *kharif* onion and intercrops like bajra + pigeon pea (2:1), sunflower + pigeon pea (3:1), cluster beans + pigeon pea (2:1) in Dhule district.

Gujarat

Rainfall was deficient in mostof the districts of Gujarattill later part of August, which adversely affected growth of the standing crops in the region. Hence, farmers were advised to provide life-saving irrigation through drip and sprinkler methods. Wherever irrigation water was not available, use of mulch with straw, groundnut shell and agricultural waste as well as spraying of Kaolin 4% solution i.e. 400 g Kaolin in 10 litres of water to reduce transpiration loss were advised. In case of complete failure of timely sown crops, sowing of contingent crops likesesame, castor, sorghum fodder, pigeon pea, soybean, green gram and black gram were suggested.

Rajasthan

Lack of sufficient rains and break in monsoon had adversely affected *kharif* crops such as jowar, maize, millet, soybean and pulses. To cope with the situation, supplementary irrigation to the standing crops were suggested, wherever feasible. Sowing of intercrops for fodder purposes, rainwater harvesting and intercultural operations to conserve moisture, better aeration, and weed Management were also advised.

Odisha

In Odisha, due to deficient rainfall in most of the districts, rice crop faced moisture stress condition. In view of continuous subdued monsoon activities in July and August, several acres of crops wilted due to lack of rainfall and rice transplanting was affected in 24 districts. The effects are clearly visible in SPI NDVI images(Fig.9.4). Subsequently, following adaptive measures were suggested to the famers:

- sowing of horse gram, black gram, maize, sesame, vegetables, fodder crops and vegetables in September in upland, where the standing crop got damaged or the landswere remained fallow,
- line sowing of pre-germinated rice seeds of varieties of 90-100 days duration by using drum seederin medium and lowland situation where transplanting could not be undertaken and
- gap filling using seedlings of the same age or clonal tillersIn lowland direct-seeded area where beushaningcould not be done.

Northeast region including Assam

The rainfall in the Northeastern part of the country were remarkably less duringMonsoon 2021. In Assam, districts like Bongaigaon, Dhubri, NC Hills, Nagaon, Darrang, Dibrugarh, Goalpara, Jorhat, Kamrup (R), Kamrup (M), Morigaon, Tinsukia and Udalguri received deficient rainfall in July. Many farmers failed to transplant rice crops in medium to upland areas in time due to prolonged dry spells.as a result, 10-20 % reduction in *Sali* rice area have been reported.However, this reduction in rainfall has not impacted the agriculture production for major crops much, since normal rainfall in these regions are quite high. Although the rainfall received was deficient in terms of its departure from normal, it was adequate to fulfil the water requirement of the crops. on the other hand, it helped to avoid crop losses due to flooding which had a positive impact on he crops.

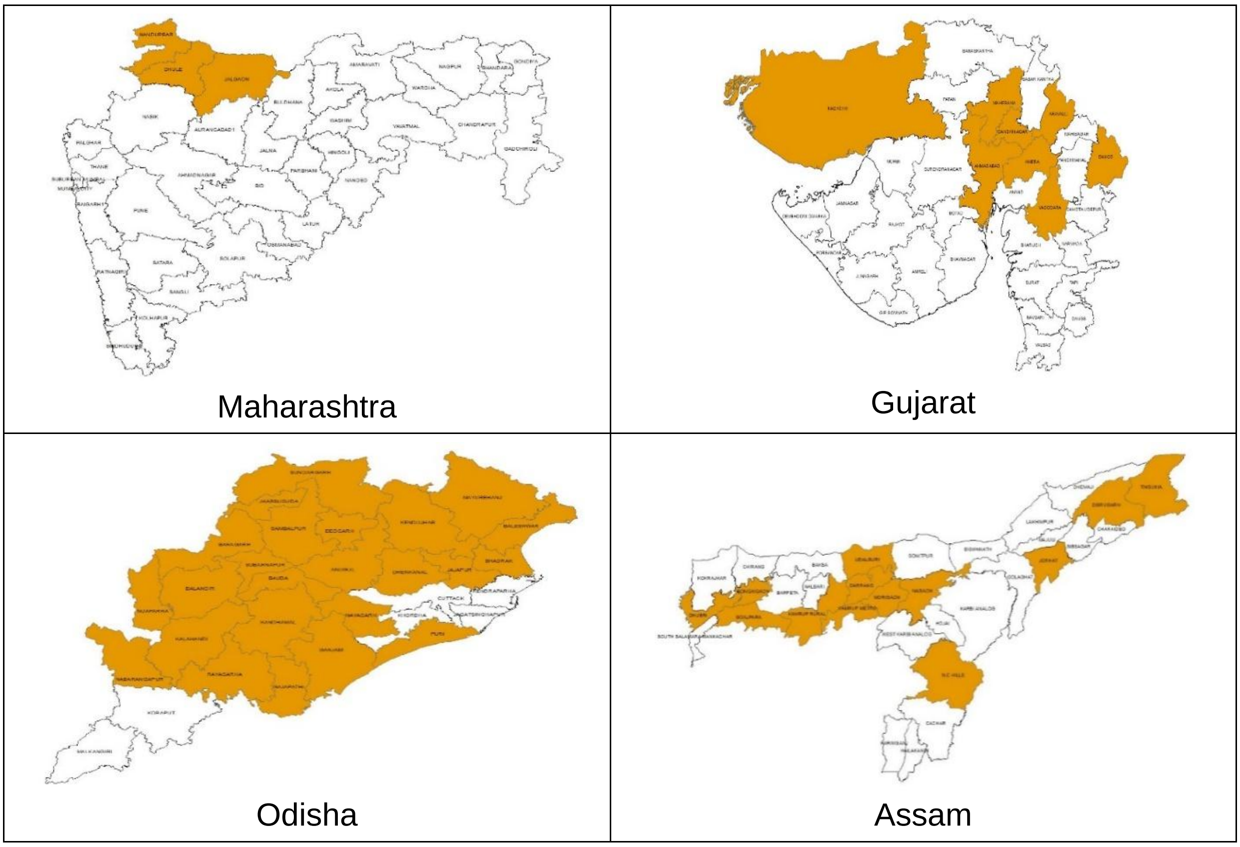

Fig. 9.3:Districtshaving impacts on crops due to deficient rain in various States during southwest Monsoon 2021.

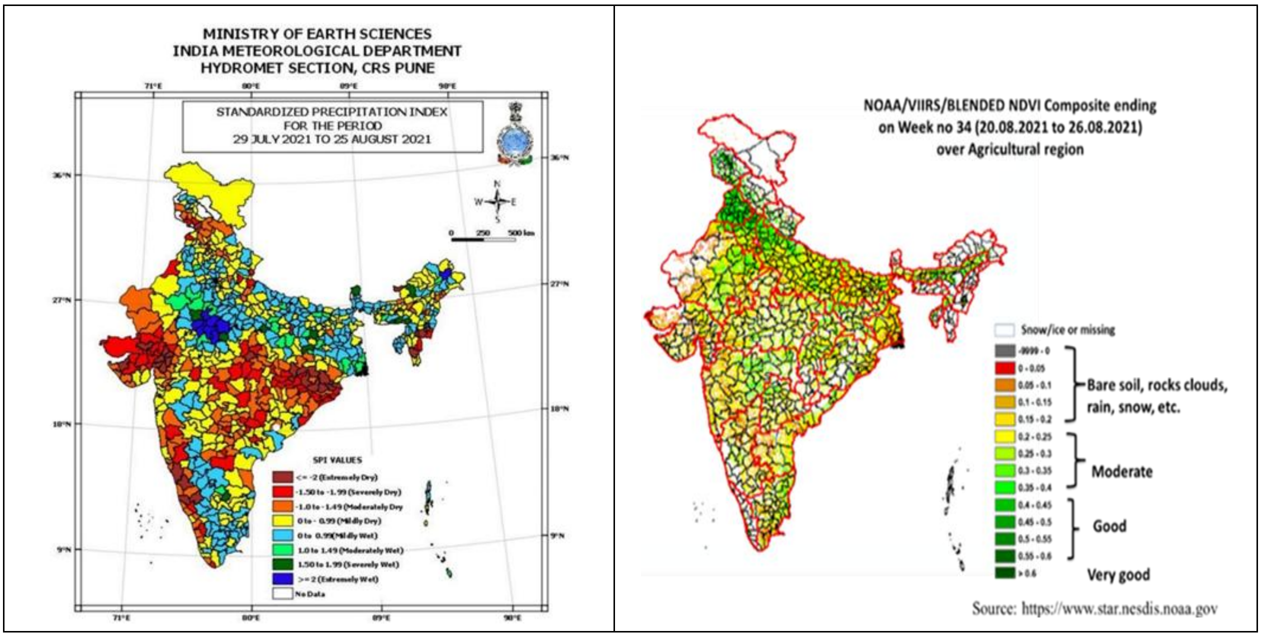

Fig. 9.4:Different Agromet products for the week ending on 26th August 2021.

b. Heavy rainfall/ Flood situationand related Agromet advisories

Several areas in the country were affected by extreme rainfall which caused flooding resulting in damage to the major crops. SPI map (Cumulative 4 weeks for the period from 2nd September to 29th September 2021) showed Extremely and severly wet conditions in different parts of the country (Fig. 9.8).Accordingly, farmers of the respective regions were provided with alert messages about the possible weather eventsalongwith appropriateagromet advisories:

i) Impact of Flood on crops

Maharashtra

Heavy rain brought floods and landslides affecting villages across the districts of Sindhudurg, Ratnagiri, Raigad and Thane in Konkan, Kolhapur, Sangli, Satara and Pune in Madhya Maharashtra and Wardha in Vidarbha region during 22th – 26thJuly 2021. Raigad, Ratnagiri, Sangli and Kolhapur districts were among the worst affecteddictricts. Crop damage due to severe flooding inPoladpurtehsil of Raigaddistrict is presented in Fig.9.5.

Flooding due to torrential rain caused damage to around 1.10 lakh hectares of the cropsduring the season across Maharashtra, according to initial estimates by the State Department of Agriculture. Almost all districts of Konkan, along with the district of Parbhani in Marathwada, had also reported crop losses. In Vidarbha, Akola, Washim and Nagpur districts had also reported crop losses.

Growth of soybean, red gram, cotton, black gram, green gram and turmeric crops had been affected in some blocks of Washim district due to waterlogging due to heavy rainfall in the second fortnight of July. Early estimates showed that around 35,000 hectares of cropped area, mainly sugarcane, had been affected by the rains in Kolhapur. Similarly, 4,500 hectares of area in Sangli and 5,000 hectares in Pune reported losses.

Fig. 9.5 :Crop damage in transplanted rice fields in Poladpur block of Raigad district, Maharashtra.

Odisha

Several districts in Odisha received heavy to very heavy rainfall during the deep depression (12th – 14thSeptember). Although there were reports of damage to several crops including vegetables at some places, these rains enrichedsoil moisture in many districts, which were facing a drought kind of situation prior to that.

Karnataka

Karnataka received heavy rainfall from 22nd Julytill 25th July 2021and the main districts affected due to floods were Uttara Kannada, Belagavi, Chikkamagaluru, Dharwad, Kodagu, Shivamogga and Haveri. Heavy rains caused extensive damage to standing crops of black gram, green gram and red gram in the above-mentioned districts.

Madhya Pradesh

Flooding and heavy rainfall affected the state since the beginning of August. As per report from various sources, heavy rains, overflowing rivers and the release of water from reservoirs collectivelyresulted in severe flooding in several villages ofShivpuri, Sheopur, Datia, Gwalior, Guna, Bhind and Morena districts.*Kharif* crops in 1,14,889 hectares area were affected by floods, causing an aggregate crop loss of Rs 577.33 crores. Standing crops over an area of 1,01,669 hectares were damaged. Soybean crop was the most affected.

Assam

As reported by The Assam State Disaster Management Authority (ASDMA), 16 districts were affected by the floods at the end of August. The worst affected districts were Lakhimpur, Majuli and Dhemaji. The flood-affected districts also includedBarpeta, Biswanath, Bongaigaon, Chirang, Dhemaji, Dibrugarh, Golaghat, Jorhat, Kamrup, Lakhimpur, Majuli, Morigaon, Nagaon, Sivasagar, Sonitpur and Tinsukia. As per ASDMA,2,937 hectares of crops were damaged due to these floodings.

Uttar Pradesh

Heavy rainfall from 15thto 19thSeptember 2021 caused flooding in several districts ofUttar Pradesh. Disaster Management Division reported floods in 13 districts of Amethi, Ayodhya, Azamgarh, Bahraich, Barabanki, Basti, Chandauli, Fatehpur, Ghazipur, Gonda, Gorakhpur, Jaunpur, Kaushumbi, Lucknow, Mirzapur, Pilibhit, Pratapgarh, Prayagraj, Rae Bareli, Sitapur and Sultanpur.The state government has pegged the crop loss around Rs. 535 crores in almost 600 villages across 24 districts.

Andhra Pradesh

Sowing was slightly delayedfor groundnut due to excess rains in June and July. Mostly cloudy weather and poor Sunshine hours during the reproductive phase of rainfed crops resulted in lower yields. Heavy rain was reported on 6thSeptember which caused a flood like situation in various districts of Coastal Andhra pradeshfrom 6thSeptember. Impacts on crops during the event are presened in Fig.9.6.

(a)

(b)

Fig. 9.6:(a) Flooded rice field in Srikakulam district and **(b)** damaged banana fields in Denkada of Vizianagaram district, Andhra Pradesh

Telangana

The spell of heavy rains on 6th September particularly in the northern parts damaged standing crops such as cotton, maize, soybean, green gram, black gram, red gram, paddy and vegetables. According to the State Agriculture Department, standing crops had been badly affected in Peddapalli, Rajanna-Sircilla, Jagityal, Kamareddy, Nizamabad, Warangal, Hanumakonda, Mulugu, Jayashankar-Bhupalapally, Mahabubabad, Jangaon, Bhadradri-Kothagudem and Khammam districts. Crops had also been impacted in Adilabad, KumaranBheem-Asifabad, Nirmal, Mancherial and a few other districts.

West Bengal

Heavy downpour during the first week of August and discharge of water from dams caused floods across the districts of PurbaBardhaman, PaschimMedinipur, Hooghly, Howrah and South 24 Parganas (Fig.9.7). During September, National and State disaster authorities reported flooding in the state after days of heavy rain from 14th September 2021. The situation was worsened after release of water from the Galudih Dam on the Subarnarekha river in Uldain the neighbouring state of Jharkhand. The most hit areas in West Bengal were PurbaMedinipur and PaschimMedinipur districts, where rivers overflowed and embankments failed. Areas of Hooghly, North 24 Parganas and South 24 Parganas districts had also been affected, mostly as a result of heavy rainfall. Extensive damage to agriculture was also reported.

Fig.9.7:Flooded rice field in coastal districts of Gangetic West Bengal.

Gujarat

The Disaster Management Division of the Ministry of Home Affairs, Govt. of India, reported on 14th September that flooding had affected 44 villages in the districts of Rajkot, Jamnagar, Porbandar, Valsad and Junagadh.

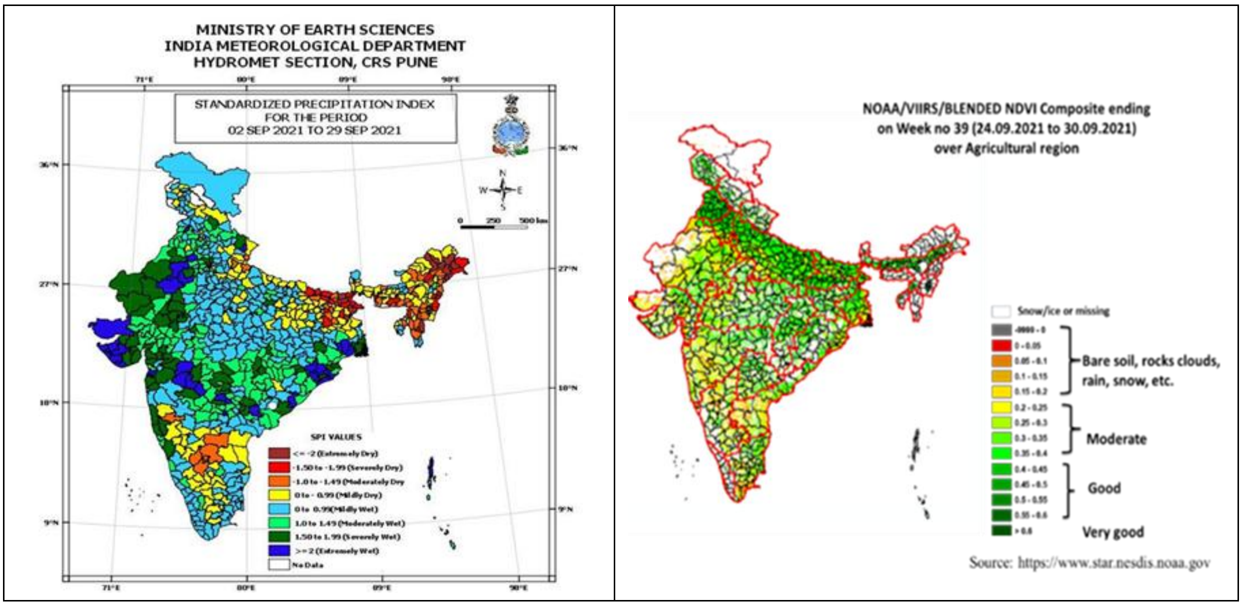

Fig. 9.8: Different agromet products for the week ending on 30th September 2021.

ii) Agromet Advisories issued for Flood affected areas

Maharashtra

In Konkan and Madhya Maharashtra region, farmers were advised to undertake following measures during heavy rainfall situation-

- drainage of excess water from the crop fields,
- application of 20% additional dose of N fertilizer and
- direct sowing of sprouted rice seeds of short duration varieties.

In Vidarbha region, due to continuous rainfall and waterlogging, wilting was noticed in cotton. Farmers were advised to spray Cobalt chloride 10 PPM @ 10g per litre of water in rows or prepare a solution of Copper oxychloride 50 PPM @ 25 g or

Carbendazim 50 WP @ 10 g + Urea 100 g + MOP 100 g per 10 litres of water and undertake drenching of above solution @ 500 ml per plant. Farmers were also suggested to undertake drenching of 2% DAP @ 200 g per 10 litres of water after 8 to 10 days.

Odisha

During heavy to very heavy rainfall due to deep depression (12th–14thSeptember), drainage of excess stagnant water from the nursery beds and fields were recommended for Boudh, Sonepur and Angul districts. However, in many rain deficient districts like Puri, Khordha, Kendrapara and Jagatsinghpur, in view of enriched soil moisture, transplanting of 45 days old seedlings for medium duration rice varieties and 50-60 days old seedlings for long-duration varieties were suggested.

Karnataka

During heavy rainfall activities from 22nd July to 25th July 2021, follwing adaptive measures were suggested:

- Draining out excess water and weed management.
- Cleaning of cradle pits, trenches to prevent water logging.
- Chemical application to avoid fruit dropping.
- Management of disease infestation e.g. black rot in coffee and arecanut, foot rot in black pepper etc.

West Bengal

Due to spells of heavy rain coupled with the release of dam water, standing crops like paddy, vegetables, betel vine and fruit crops were damaged.

In the Coastal Saline Zone of West Bengal (PurbaMedinipurand South 24 Parganas districts),farmers were advised to drain out excess water immediately from the rice nurseries, to save seedlings of*Aman* rice,and also from the main field, where transplanting was already completed. In the fully damaged rice field, re-transplantingof rice seedlings were recommended after receding of flood water.

Flood in coastal districts also damaged rice nurseries;farmers were advised to undertake nursery sowing in the comparatively upland areas with short duration varieties (115-120 days), with the objective of transplanting in the earlier part of September. After removal of excess water from the seedbed,application ofUrea @400g and Muriate of Potash (MoP) @150g per kathawas suggested for the nourishment of damaged seedlings.Alternatively in affected fields, cultivation of leafy vegetables, pumpkin, gourd and sowing of*vadukalai* wererecommended.

Assam

After receding of floodwater during the last part of August in chronically flood-affected areas, farmers were advised to transplant seedlings of rice varieties, namely, MonoharSali, Solpona, Govindabhog, Gitesh, Prafullaand other traditional high yielding late Sali rice varieties. For aged seedlings, transplantingwith higher number of seedlings per hill with closer spacing was recommended. A few advisories arementioned below:

- In flood-affected areas of the North Bank Plain Zone, farmers were advised for direct sowing of the sprouted seeds of very short duration (less than 100 days) photo-insensitive varieties.
- In Upper Brahmaputra Valley Zone, nursery raising of recommended Sali rice varieties like Monoharsali, Salpona, Prasadbhog, Gobindabhog etc. or very short duration varieties like Luit, Kapilee and Dishangwere suggested.The seeds of these varieties could be sown in the nursery beds till 1stweek of August.

Gujarat

In Rajkot district and in North Saurashtra zone, farmers were advised to drain out excess water immediately from the low-lying fields to prevent wilting in all crops arising due to continuous rain and wet conditions. For those regions, wheresevere damage and wilting have been reported, sowing of alternate crops likeAjwain, suwa, castor, sesame and chickpea were advised. Postponement of harvesting of bunch groundnut, sesame and pearl millet was alo suggested.

B) Severe Cyclonic Storm 'Gul Aab' (24th – 28thSeptember 2021)

The cyclonic storm "Gul Aab" crossed North Andhra Pradesh and adjoining south Odisha coasts near 18.4°N/84.2°E about 20 km north of Kalingapatnam with a wind speed of 75-85 gusting to 95 kmph during 1930-2030 IST of 26thSeptember. Further moving westwards, it weakened into a deep depression over North Andhra Pradesh and adjoining south Odisha in the early hours (0230 IST) of the 27thSeptember 2021. Because of the Severe Cyclonic Storm, alerts and warnings along with the appropriate agromet advisories were prepared and issued by the concerned Agromet Field Units (AMFUs) and District Agromet Units (DAMUs). These alerts and warnings along with Agromet Advisories were disseminated to the farmers in the respective states *viz.*, Andhra Pradesh, Odisha, West Bengal, Telangana, Chhattisgarh, Maharashtra and Gujarat through multichannel dissemination systemincluding SMS through mKisan portal of the Ministry of Agriculture (84.54 lakh farmers) and social media like WhatsApp (2.78 lakhfarmers).

i) Advisories issued before the cyclonic storm

Andhra Pradesh and Odisha

Due to passage of cyclone 'GULAAB', heavy rainfall and high wind speed were expected in north coastal Andhra Pradesh (Srikakulam, Vizianagaram and Visakhapatnam districts) and Ganjam, Gajapati, Khordha, Puri, Raigada&Koraput, Navrangpur&Malkangiri districts of Odisha on 25th& 26thSeptember, farmers were advised –

- Draining out excess water from the crop fields of rice, sugarcane, maize, bajra, fingermillet, groundnut, Cotton, Redgram, Vegetables and orchards..
- Postponement of harvesting of matured crops and if already harvested, keeping harvested produce at safer places.
- Postponement of the spraying of chemicals and fertilizer applications.
- Undertake propping in sugarcane, banana and papaya to avoid lodging due to ensuing squally winds.
- Protection of vegetable seedlings from rainfall.
- Covering the nursery beds with polythene.

- Temporarily withholding the sowing of non-paddy crops.
- To keep the furrow weed-free for easy run-off of excess water.
- Staking in vegetables.
- Avoiding tying the cattle under trees or near any big tree and procuring food for atleast next three days.

Maharashtra

- Draining out excess water from soybean, *kharif*sorghum, pearl millet, *kharif* groundnut, ginger, turmeric, vegetables, citrus and pomegranate orchard.
- Immedite harvesting of matured vegetable crops.
- Immedite harvesting of black gram and green gram crop and keeping harvested produce in safe places.
- Keeping the cattle inside.

ii) Post-Cyclone Remedial Measures

The following Post-Cyclone remedial measures were advised to the farmers in Odisha, North Andhra Pradesh, Telangana, Chhattisgarh and Maharashtra-

- Raising the lodged canes and banana and lifting the lodged rice and finger millet and tie 2-3 hills.
- Chemical applications for disease and pest management e.g. bacterial leaf blight, sheath rot disease etc.
- Booster doses of fertilizers.
- Providing mechanical support to fruit and vegetable plants.
- Foliar spray of micronutrients immediately after cessation of cyclone.

9.3: Incidence of pest and disease during southwest Monsoon (*kharif* season) 2021

During the season, no major outbreak of pests and diseases had been reported. However, a few advisories issued by AMFUs and DAMUs have been presented below:

- Incidence of stem borer in rice was reported above ETL in Nellore district of Andhra Pradesh during first fortnight of July. Suitable control measures had been advised through agromet advisories by the AMFU like application of Carbofuran 3G granules @ 10kg/acre or Cartap Hydrochloride 4G granules @ 8 kg/acre when the crop wasat 25-30 DAT and spraying ofCartap Hydrochloride @2 g/litre or Chlorantraniliprole @ 0.4 ml/litre of water when the crop wasat 40-45 DAT.
- In Central Brahmaputra Valley Zone of Assam, high temperature after continuous rainfall for long period (1 to 2 weeks) during August was very conducive for more infestation of rice Hispa; to control rice hispa along with other insects like leaf folder, case worm etc. during tillering stage, spraying of Chlorpyriphos 20EC or Monocrotophos 40EC @ 1.5ml per litre of water was advised.
- In High Hill Temperate Dry Zone of Himachal Pradesh, frequent rain in the valley (third week of August), was conducive for spreading of late blight disease in potato.Spraying ofRidomil @2.5g-3g/litre or Copper Oxychloride @2.5g-3g/litre of water was recommended.
- In West Vidarbha region of Maharashtra, in cotton crop at flowering stage (first week of September), weather was favourablefor incidence of pink bollworm larvae within flowers;farmers were advised to collect and destroy flowers/buds and spray Quinalphos 25% AF @ 25 ml or Chlorpyriphos 20% EC @ 25 ml per 10 litres of water during clear weather.

9.4: Impact of Monsoon 2021 on Crop Production

First Advance Estimates of production of major *kharif*crops for 2021-22 have been released by the Ministry of Agriculture and Farmers Welfare on 21stSeptember

2021. The production of most of the *kharif* crops for the agricultural year 2021-22 hadbeen estimated higher than their normal production.

- As per First Advance Estimates for 2021-22 (*kharif*only), total **foodgrain** production in the country wasestimated at record 150.50 million tonnes which is higher by 12.71 million tonnes than the average foodgrain production of previous five years (2015-16 to 2019-20).
- Total production of *kharif* rice during 2021-22 was estimated at 107.04 million tonnes. It is higher by 9.21 million tonnes than the previous five years' (2015-16 to 2019-20) average *kharif*rice production of 97.83 million tonnes.
- Production of *kharif*coarse cereals wasestimated at 34.00 million tonnes which is higher by 2.11 million tonnes than the average production of 31.89 million tonnes.
- Total *kharif*pulses production during 2021-22 was estimated at 9.45 million tonnes. It is higher by 1.39 million tonnes than the average pulses production of 8.06 million tonnes.
- Total *kharif*oilseeds production in the country during 2021-22 was estimated at 23.39 million tonnes which is higher by 2.96 million tonnes than the average oilseeds production of 20.42 million tonnes.
- Total production of sugarcane in the country during 2021-22 wasestimated at 419.25 million tonnes. The production of sugarcane during 2021-22 is higher by 57.18 million tonnes than the previous five years' (2015-16 to 2019-20) average sugarcane production of 362.07 million tonnes.
- Production of cotton has been estimated at 36.22 million bales (of 170 kg each) and production of Jute & Mesta estimated at 9.61 million bales (of 180 kg each).

The production of most of the crops for the *kharif* season 2021 has been estimated higher than their normal. However, *kharif* crops like soybean and cotton, the actual production for the current year may be less than the advance estimates. The soybean crop got damaged due to whichyield may drop in the States like Madhya Pradesh and Maharashtra. Weak rainfall in the critical crop growing period of soybean during first half of July and further excessive rainfall in September are likelywould impact yield negatively in Madhya Pradesh. Submergence due to unprecedented rainfall in Marathwada has damaged soybean crop at pod development/maturity stage. Heavy rains due to Cyclone Gulab in Telangana, Maharashtra, Gujarat, Madhya Pradesh and Chhattisgarh had damaged standing cotton crop at many places due to boll rotting.

IMD issued appropriate alerts and warnings along with Agrometadvisories based on the medium range weather forecast as well as the extended range weather forecast to the farming community to deal with the impact of adverse weather situations. Farmers could take advantage of these agrometadvisories to take appropriate farm management decisions in time which has improved agricultural situations under extreme weather conditions resulting in higher crop production as compared to earlier years.

9.5 : Success Stories from the Farmers

1.	 Shri DipaksinghGautam	Shri DipaksinghBabasahebGautam from Zari village, Tal & Dist. Parbhani, (Marathwada region of Maharashtra) was benefitted by receiving timely forecast of rainfall alongwith advisory regarding harvesting of matured soybean on 8th October 2021 so that he managed to save his 30 acre soybean and saved approximately Rs. 13,50,000/- (Thirteen Lakh Fifty Thousand).

2.	 Shri Ritesh Singh Rajpoot	Shri Ritesh Singh Rajpoot is a marginal farmer from Aron block, Dist- Guna (Madhya Pradesh). By adopting Agromet Advisory services, he managed to save yield losses due to adverse weather condition and benefited with crop intensification than other non AAS farmers. He was benefited with enhanced income of Rs. 414500/- during the year 2020-21.
3.	 Shri SudhansuNayak	Shri SudhansuSekharNayak, Sankilo, Nischintakoili, Dist- Cuttack (Odisha) had cultivatedvegetables and onion in 2 acres and rice in one acre of land.His total crop production was enhanced after following AAS bulletins and input cost was minimized@ Rs. 3000/- in labour due to timely labour operation based on rain forecast. He also saved Rs.1200/- in irrigationalongwithRs. 20,000/- due to preharvesting of vegetables as per rainfall forecast.
4.	 Shri BijendraKashyap	Shri BijendraKashyap from ChauderaChauderi village, Tilhar block, Dist. Shahjahanpur (Uttar Pradesh)plans his farm operatationson the basis of weather forecast. Based on the Agromet advisories dated 19th August 2021,he saved the cost of irrigation and saved a total ofRs. 4500/-in 9 acres of paddy and sugarcane crops.

10

VERIFICATION OF HEAVY RAINFALL WARNINGS-MONSOON 2021

(K.Sathi Devi and Naresh Kumar, NWFC, IMD, New Delhi)

10.1 Introduction

Southwest Monsoon season which consists of four months from June to September is the major rainfall season for the country. The normal date of monsoon onset over Kerala is 1st June and it takes more than one month to cover the entire country. In general, monsoon starts its withdrawal from Northwest India by the middle of September and it withdraw from the entire country around the middle of October. Thus the duration of monsoon over different parts of the country is different however the period from 1st June to 30th September is considered as the Southwest monsoon season for the country as a whole and the rainfall occurring during this period is considered as the monsoon seasonal rainfall for preparation of rainfall statistics and for verification of forecast etc.

During monsoon season, different parts of the country experience heavy to very heavy and extremely heavy rainfall leading to floods, damage to crops, landslides etc. affecting the public at large.

India Meteorological Department issues forecast and warnings with colour code for the spatial distribution and intensity of rainfall for next five days with an outlook for another two days and the same are disseminated to the users including disaster management authorities at the Central and State levels through various modes. From National Weather Forecasting Centre (NWFC), these warnings are issued in the sub divisional scale whereas from the Regional and State Meteorological Centres the forecasts and warnings are issued in the district scale.

In order to improve the quality of the forecast and warnings, it is necessary to verify the warnings issued with the observed weather hence India Meteorological

Department verifies all the forecasts and warnings issued on regular basis and document the same for record purpose and for future reference.

In this report, the heavy rainfall warnings issued during the monsoon season 2021 are verified and the important features are brought out.

10.2. Heavy rainfall Events

The twenty four hour accumulated rainfall of a day is the total rainfall observed from 0830 hrs of the previous day to 0830 hrs IST of that day. The terminology used to represent intensity of rainfall is given in Table 10.1 below.

Table 10.1: Terminology for intensity of 24 hour accumulated rainfall

S No.	Terminology	Rainfall(mm)	Rainfall (cm)	Percentile
1	Very light rainfall	Trace -2.4		
2	Light rainfall	2.5-15.5	Upto 1	Upto 65
3	Moderate rainfall	15.6-64.4	2-6	65-95
4	Heavy Rainfall	64.5- 115.5	7-11	95-99
5	Very Heavy Rainfall	115.6-204.4	12-20	99.0-99.9
6	Extremely Heavy rainfall	Greater than or equal to 204.5 mm	21 cm or more	>99.9
7	Exceptionally Heavy Rainfall	When the rainfall observed is a value near about the highest recorded rainfall at or near the station for the month or the season. However, this term will be used only when the actual rainfall amount exceeds 12 cm.		

IMD issues heavy rainfall warning when the accumulated rainfall for the day is expected to be 64.5 mm or more (7 centimeters or more).

The details of heavy rainfall and above, very heavy rainfall and above and that of extremely heavy rainfall for all the subdivisions of the country for the months of June, July, August and September and for the monsoon season as a whole during 2021 are given in the Annexure I, II and III respectively.

From Annexure I, it is found that, during monsoon season 2021, there had been a total number of 1870 rainfall events with heavy rainfall or more for the country as a whole with the highest number of 559 events reported in the month of July. In 2021, during the month of September, enhanced monsoon activity had been there and a total number of 465 events with heavy rainfall or more had been reported during the month. If the subdivision wise distribution of events is considered, the highest numbers of 84 events were reported from Assam & Meghalaya whereas Odisha, Bihar, East Uttar Pradesh, West Madhya Pradesh, Konkan & Goa and Chhattisgarh reported 70 or more number of heavy rainfall events. Even the rain shadow region of Tamil Nadu also received 73 events during the season. The lowest number of 3 events had been reported from Lakshadweep followed by 19 events from Jammu Kashmir & Ladakh.

In the month of June, Assam & Meghalaya reported the maximum number of 27 events followed by Konkan & Goa with 23 events whereas Jammu Kashmir & Ladakh reported the minimum with one event.

In the month of July, Assam & Meghalaya recorded a total number of 24 events followed by Bihar, Tamil Nadu, Puducherry & Karaikkal, Coastal and South Interior Karnataka reporting 22 events each. Lakshadweep Islands with 0 events reported the lowest during the month.

In the month of August, the highest number of 29 events was reported from Bihar followed by 25 events from Assam & Meghalaya. In this month also Lakshadweep recorded the lowest number of 1 event followed by Jammu Kashmir & Ladakh, Saurashtra & Kutch and Rayalseema with 2 events each.

In the month of September, the maximum number of 25 events had been reported from Gujarat Region followed by 23 and 22 events from West Madhya Pradesh and East Rajasthan. Lakshadweep with NIL events followed by Jammu Kashmir & Ladakh with 2 events were the lowest.

As mentioned earlier, details of rainfall events with the intensity of very heavy and above are given in Annexure II. There had been a total number of 683 such events during the season for the country as a whole. The maximum number of 236 events were reported in the month of July followed by 159 events in September whereas June and August reported a total number of 142 and 146 events respectively. Assam & Meghalaya, East Uttar Pradesh and Konkan & Goa reported 40 or more number of such events during the season with the highest number of 46 events reported from Assam & Meghalaya. Lakshadweep reported NIL events whereas Jammu Kashmir and Ladakh reported 4 events among the minimum.

In the month of June, maximum number of 14 events was reported from Assam & Meghalaya followed by 13 events from Konkan & Goa and 12 events from Bihar whereas Nagaland, Manipur, Mizoram & Tripura, Haryana, Chandigarh & Delhi, Punjab, Himachal Pradesh, Jammu Kashmir & Ladakh, West Rajasthan, Marathwada, Vidarbha, Coastal Andhra Pradesh & Yanam and Lakshadweep reported NIL events.

In the month of July, Coastal Karnataka recorded the highest number of 17 events followed by Konkan & Goa with 14 events and West Madhya Pradesh and Madhya Maharashtra with 13 events each. Lakshdweep with NIL events along with Nagaland, Manipur, Mizoram & Tripura, Jharkhand, Coastal Andhra Pradesh & Yanam, Rayalseema and North Interior Karnataka with 2 events each reported the minimum events during the month.

In the month of August, Assam & Meghalaya recorded the maximum number of 16 events followed by East Uttar Pradesh with 15 and Sub Himalayan West Bengal & Sikkim with 14 events.Jammu Kashmir & Ladakh, Himachal Pradesdh, Vidarbha Rayalseema, North Interior Karnataka and Lakshadweep reported NIL events during the month.

In the month of September, the maximum number of 13 events were reported from Gujarat Region followed by 11 events each from Odisha and Konkan & Goa. Jammu Kashmir & Ladakh and Lakshadweep reported NIL events during the month.

If the details of extremely heavy rainfall events during monsoon season 2021 (given in Annexure III) is considered, it is found that, there had been a total number of 122 such events during the season. Maximum number of 48 extremely heavy rainfall events occurred in the month of July whereas there had been about 25 events each during the other three months of the season. Konkan & Goa reported the maximum number of 18 events for the season followed by Assam & Meghalaya with 13 events. Nine sub divisions viz. Andaman & Nicobar Islands, Arunachal Pradesh, Nagaland, Manipur, Mizoram & Tripura, Punjab, Marathwada, Vidarbha, Chhattisgarh, Kerala & Mahe and Lakshadweep had not reported any extremely heavy rainfall events during the season.

Konkan & Goa recorded the maximum number of 8 events in the month of July followed by 6, 3 and 1 event in the month of June, September and August respectively. In case of Assam & Meghalaya, the maximum number of 7 events occurred in the month of August. During the month of September, the maximum number of 4 events had been reported from Gujarat Region.

10.3. Verification of Forecast

IMD issues forecast and warnings for five days on daily basis. From NWFC, these forecasts and warnings are given for the country as a whole in the sub divisional scale (for the 36 subdivisions) and from RMCs/MCs, they are given in the district level for their concerned area of responsibility. In this document, the verification pertaining to heavy rainfall warnings in the sub divisional scale issued from NWFC are presented. Even though the NWFC forecasts are updated four times a day, verification presented here is for the main forecast issued based on the observations of 00 and 03 UTC.

Forecasts issued for Day 1 (D1) corresponds to the weather expected during next 24 hrs period, Day 2 (D2) for the period between 24 to 48 hrs, Day 3 (D3) for the period between 48 to 72 hours, Day 4 (D4) for the period between 72 to 96 hours and Day 5 (D5) for the period between 96 to 120 hrs.

Meteorological day is considered from 0830 hrs IST of the concerned day to 0830 hrs IST of the next day.

Four verification indices viz. Probability of Detection (POD), Critical Success Index (CSI), False Alarm Rate (FAR) and Missing Rate (MR) are considered for the verification of the heavy rainfall warnings issued during the monsoon season 2021.

In order to define these indices, four possibilities of the forecasted and observed weather need to be considered.

If the heavy rainfall warning is issued and it is realised it corresponds to Hits (A)

If the heavy rainfall warning is not issued but it is realised it gives the Miss (B)

If the heavy rainfall warning is issued and it is not observed it corresponds to False Alarm(C)

If the heavy rainfall warning is not issued and it is not realised also, it gives the Correct Non-occurrence (D). These are projected in the contingency table below.

OBSERV ED	**FORECAST**	
	YES	**NO**
YES	**A**	**B**
NO	**C**	**D**

Accordingly, the indices are defined as below:

Probability of Detection (POD) = A/ (A+B)

False Alarm Rate (FAR) = C/(C+A)

Missing Rate (MR) = B/ (A+B)

Critical Success Index (CSI) = A/ (A+B+C)

For best/perfect forecast, POD and CSI will be equal to 1 and MR & FAR will be zero.

10.4. Verification of Heavy rainfall Warnings of Monsoon Season 2020

As per practice, the warnings are issued for different categories of intensity of rainfall viz. heavy rainfall (7-11 cms), very heavy rainfall (12-20 cms) and extremely heavy rainfall (21 cms and above) as and when the situation demands. However, the verification presented here considers the warnings issued for the rainfall of 7cms or more taken altogether rather than for each category.

NWFC issues warnings in the sub divisional scale for the country as a whole. The verification is carried out in subdivisional scale and are presented here for All India (for all the 36 subdivisions taken together) as well as for the six regions. The subdivisions pertaining to each region are given in Table 10.2.

Table 10.2: Area of Responsibility of Regional Meteorological Centres

Region	Responsible Regional Met Centre	Subdivision
Northeast India	RMC, Guwahati	Arunachal Pradesh, Assam & Meghalaya, Nagaland, Manipur, Mizoram & Tripura
East India	RMC, Kolkata	Bihar, Jharkhand, Sub-Himalayan West Bengal & Sikkim, Gangetic West Bengal, Odisha, Andaman & Nicobar Islands
Northwest India	RMC, Delhi	Jammu Kashmir & Ladakh, Himachal Pradesh, Uttarakhand, Punjab, Haryana, Chandigarh & Delhi, West Uttar Pradesh, East Uttar Pradesh, West Rajasthan, East Rajasthan
West India	RMC, Mumbai	Gujarat Region, Saurashtra & Kutch, Madhya Maharashtra, Marathwada, Konkan & Goa
Central India	RMC, Nagpur	West Madhya Pradesh, East Madhya Pradesh, Vidarbha, Chhattisgarh
South Peninsular India	RMC, Chennai	Coastal Andhra Pradesh & Yanam, Telangana, Rayalaseema, Coastal Karnataka, North Interior Karnataka, South Interior Karnataka, Tamilnadu, Puducherry & Karaikal, Kerala & Mahe, Lakshadweep

10.5. Results and Discussion

10.5.1. Heavy Rainfall Verification (Regional Basis)

Verification of heavy rainfall warnings carried out by NWFC for each region and for the country as a whole is presented in Figure 10.1 to Figure 10.7.

Figure 10.1 corresponds to the plot of verification indices viz. FAR, MR, CSI and POD for Northeast India for Day 1 to Day 5 forecasts. From the figure it is seen that the POD is 83% for Day1 forecast. It deceases with the increase in the lead period of the forecast but is more than 60 % till Day 4 forecast. CSI is more than 50% till Day 3 forecast and it decreases from 56% to 53% from Day 1 to Day 3. The MR is increasing with the lead period of the forecast from 17% for Day 1 to 45% for Day 5. The FAR is found to be very large for the region and it is decreasing with increase in lead period of forecast. It has a value of 52 % for Day 1 forecast itself.

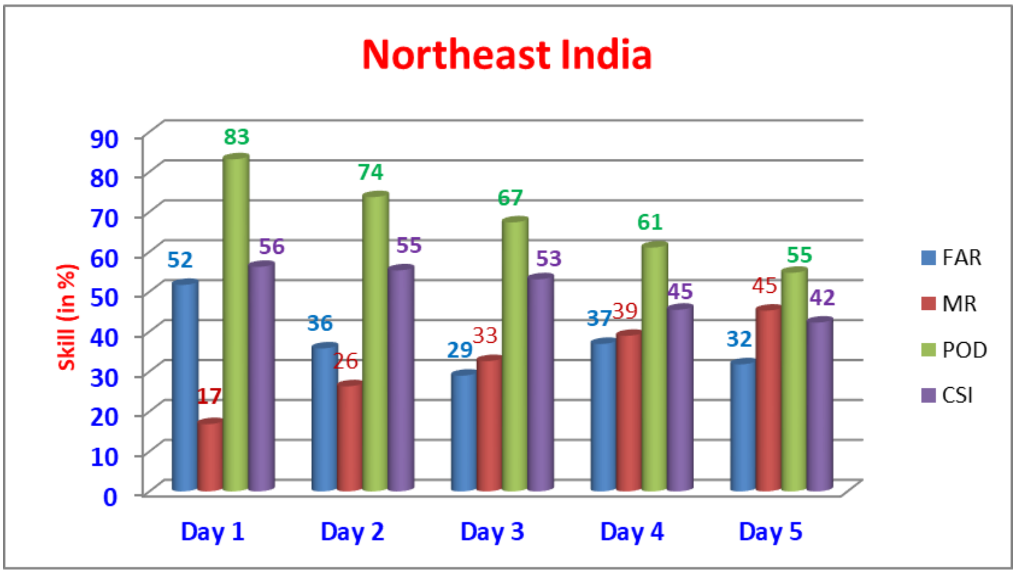

Figure 10.1: Verification indices for Northeast India

Figure 10.2 corresponds to the plot of verification indices for East India. Here the value of POD for Day 1 is 77 % and it shows decrease from Day 2 to Day 5 but is almost consistent for Day 2 to Day 4 and is 64%, 63% and 60% respectively for these days. CSI more than 50% is there for Day 1 forecast only (55%). Missing rate increases with lead period of forecast from 23% for Day 1 to 47% for Day 5. FAR is 34% for Day 1 and it decreases from 30% for Day 2 to 21% for Day 5.

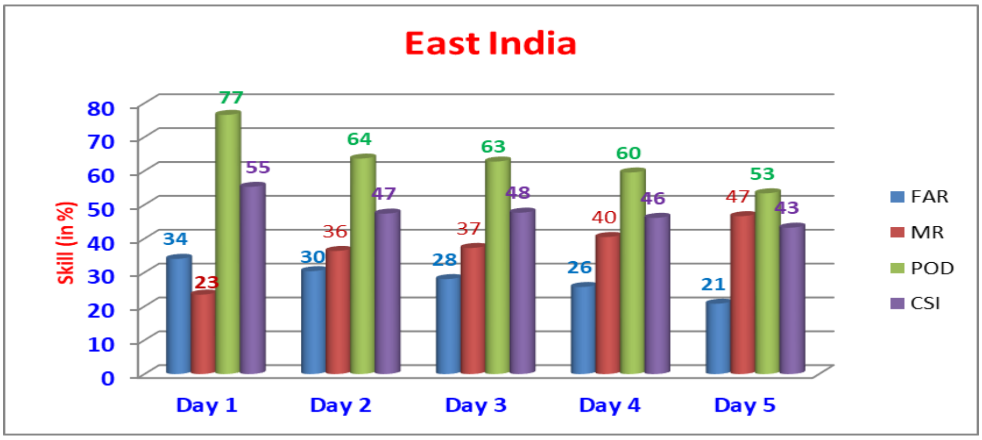

Figure 10.2: Verification indices for East India

Figure 10.3 corresponds to the verification indices for Northwest India for Day 1 to Day 5 forecasts. Here, the value of POD is less than 70 % and is only 67% for Day1 itself and it is 60% and 58 % for Day 2 and Day 3 forecasts and 55 % and 53% for Day 4 and Day 5 forecasts respectively., The CSI value for Day 1 is 50% and it is decreasing from 46 to 41% from Day 2 to Day 5. The FAR is less than 20% for all the days of forecast with the highest being 19% for Day 1. The MR is found to be high for Day 1 (33%) and it is increasing with lead period of forecast and attaining a value of 47% for Day 5.

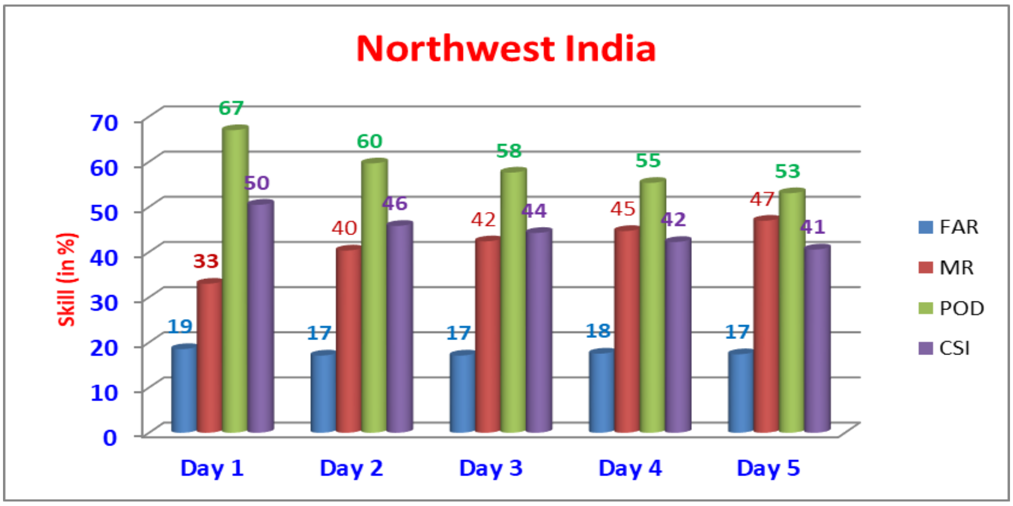

Figure 10.3: Verification indices for Northwest India

Figure 10.4 corresponds to West India. Here, the POD is 80% for Day 1 forecast. POD is found to be decreasing with the increase in lead period of forecast but it is about 60% or more till Day 3 forecast. For this region, the value of CSI is 50 % or more till Day 3 with the maximum of 61% for Day 1 forecast. The FAR is about 25% for Day 1 forecast itself. The MR is also about 20 % for this region for Day1 forecast and it is steadily increasing from Day 2 to Day 5 and reaching 48% for Day 5 forecast.

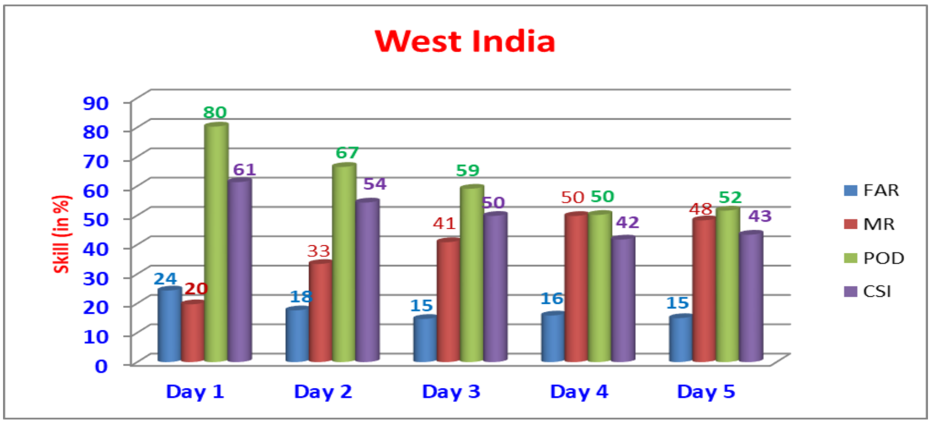

Figure 10.4: Verification indices for West India

Figure 10.5 corresponds to the verification for Central India. Here the POD is 75% for Day 1 forecast and it is 65% for Day 2 and Day 3 forecasts. It is decreasing then but is more than 50% for Day 4 and Day 5 forecasts. The CSI values are found to be more than 50% till Day 3 forecast. For this region the FAR is more than 20% for the whole period of forecast but it is almost steady. The MR is 25 % for Day 1 forecast and it is increasing and reaching a value of 47% for Day 5 forecast.

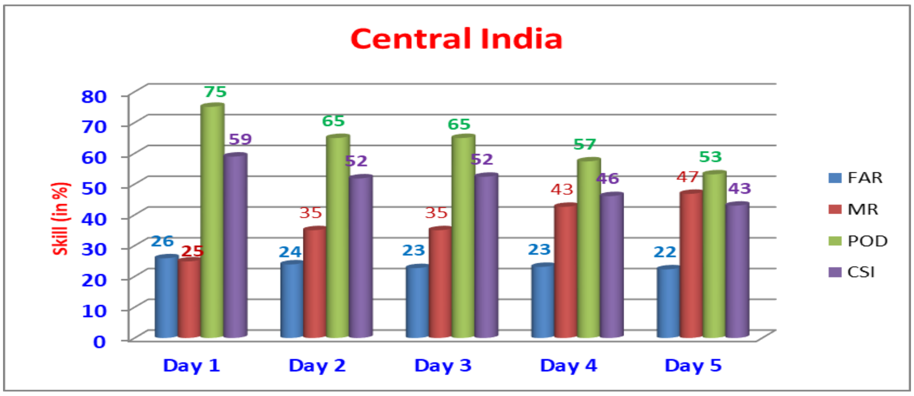

Figure 10.5: Verification indices for Central India

Figure 10.6 corresponds to the verification results for South India. Here, the POD is 71% for Day 1 forecast and it is decreasing with the increase in lead period of forecast. The CSI is more than 50% for Day 1 only and it is less than 40 % for Day 4 and Day 5 forecasts. The FAR is 25% for Day 1 forecast itself. The MR is about 30 % for Day 1 forecast itself and it is increasing and reaching 55% for Day 5 forecast.

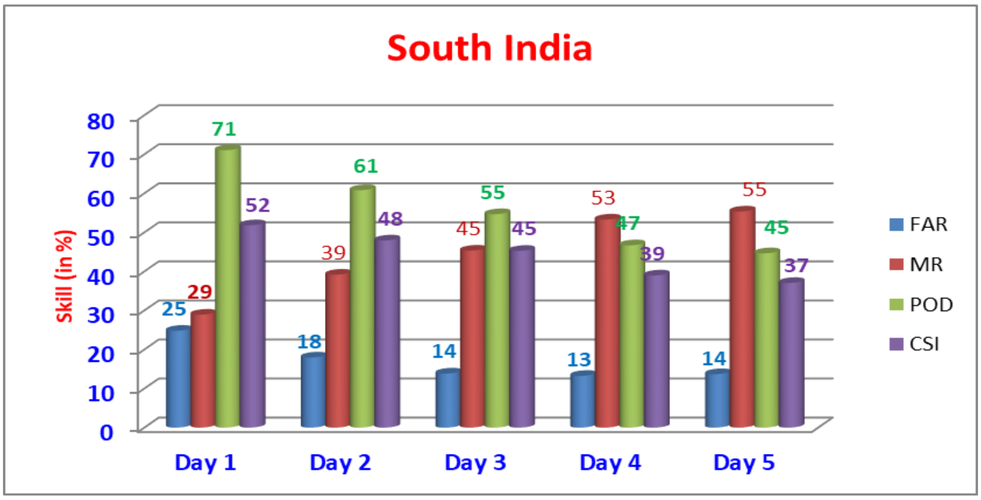

Figure 10.6: Verification indices for South India

10.5.2 Comparison of Regional forecasts:

If the forecast performance of different regions is compared, all the regions excluding Northwest India have POD of 70% or more for Day 1 forecast. The highest value of 83 % is there for Northeast India followed 80% for West India. Northwest India has the lowest value of 67% for Day 1 forecast. With the increase in lead period of forecast, the POD values are decreasing for all the regions and the lowest POD for Day 5 forecast is for South India with a value of 45%. Even though POD for Day 1 forecast is the lowest for Northwest India, the decrease in POD with the increase in lead period of forecast is gradual for this region.

CSI values are 50% or more for West, Central and Northeast India till Day 3 forecast whereas it is 50 % or more only for Day 1 forecast for the remaining three regions.

FAR is maximum for Day 1 forecast and it is decreasing from Day1 to Day 5 for all the regions. The highest value of FAR for Day 1 forecast is for Northeast India (52%) followed by East India (34%). Northwest India got the lowest value of FAR for Day 1 forecast (19%) and its value is almost steady with the increase in lead period of forecast for this region.

The MR is found to be increasing from Day 1 to Day 5 and Northwest India has the maximum MR (33%) for Day 1. The MR for Day 5 is maximum for South India (55%) whereas it is about 47% for all the other regions.

10.5.3. Heavy Rainfall Verification (All India)

Figure 10.7 corresponds to the verification of heavy rainfall warning for All India weather forecast considering all the subdivisions taken together. The POD for All India Day 1 forecast is 74% and it is 60% or more up to Day 3. The CSI value is 55% and 50% respectively for Day 1 and Day 2 forecasts but is gradually decreasing and reaching 41% for Day 5. The FAR has the value of 26 % for Day 1 forecast and it is almost steady for Day 2 to Day 5 with values close to 20%. The MR for Day 1 itself is 26% and it is steadily increasing and reaching almost 50 % for Day 5.

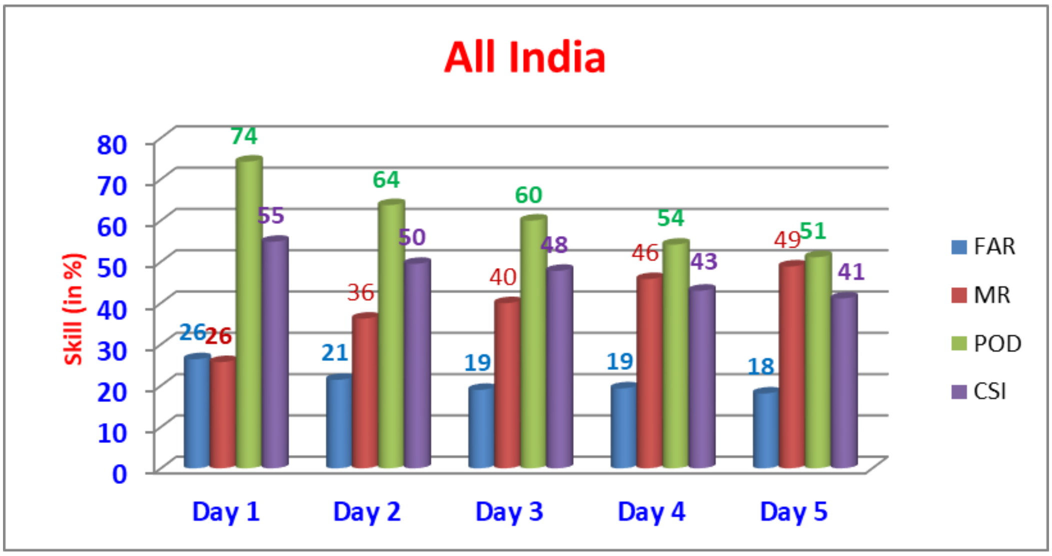

Figure 10.7: Verification indices for All India

Figure 10.8 corresponds to the comparison of average values of verification indices for the period 2012-2016 with that of 2017-2021 in respect of Missing Rate (MR), Probability of Detection (POD) and Critical Success Index (CSI) of Day 1 forecast. It is found that the Missing rate, Probability of Detection and Critical Success Index show an improvement of 47%, 52% and 32 % respectively during the time span of 2017-21 in comparison with the average values of those indices for 2012-2016 which clearly points out the betterment in the accuracy of forecast in the recent years.

Figure 10.8: Improvement in heavy rainfall forecast

The modernisation programme of IMD including enhancement of observational system leading to better initial conditions, improvements in Numerical Weather Prediction models and capacity building of the workforce giving rise to better understanding of the latest developments and techniques in the field led to the improvement in the forecast projected above.

10.6. Summary and Conclusion

In this document, the heavy rainfall events of Monsoon Season 2021 are analysed and the warnings issued for heavy rainfall and above for the season are verified and the results are presented. The Probability of Detection, Critical Success Index, False Alarm Rate and Missing Rate are computed regional wise as well as All India basis for the sub divisional forecast and the results are compared. Also the average values of verification indices for Day 1 forecast (All India Warning) for the period 2012-2016 are compared with that for the period 2017-2021 and the results are presented.

The important points are summarised below:

I. There had been a total number of 1870 events of heavy rainfall and above during Monsoon season 2021 out of which 683 had been very heavy rainfall and above and 122 had been extremely heavy rainfall. The maximum events of heavy rainfall and above, very heavy rainfall and above and extremely heavy rainfall had occurred in the month of July.

II. Assam and Meghalaya recorded the highest number of events in the categories of heavy rainfall and above and very heavy rainfall and above (84 and 46 respectively) whereas Konkan & Goa recorded the highest number of extremely heavy rainfall with 18 events during the season. Lakshadweep recorded the lowest number of 3 events during the season which were of heavy rainfall category only.

III. The rain shadow area during monsoon season viz. Tamil Nadu, Puducherry & Karaikkal recorded maximum number of 73 events during the season out of which two were extremely heavy rainfall events. During Monsoon season 2021, Kerala & Mahe had not recorded any extremely heavy rainfall events.

IV. For All India basis, the POD is maximum for Day1 forecast (74%) and it is decreasing to Day 5. The CSI values are 55% and 50% respectively for Day 1 and Day 2 forecasts after which it is decreasing and reaching 41% for Day 5 forecast. The FAR is highest for Day 1 (26%) and it is close to 20% from Day 2 to Day 5. The MR is 26% for Day 1 forecast and it is steadily increasing and reaching 49 % for Day 5 forecast.

V. If the Probability of Detection for different regions is considered, all the regions have POD more than 60% for Day 1 forecast. The highest value for Day 1 is 83% for Northeast India followed by 80 % for West India. The lowest value of POD for Day 1 forecast is 67% for Northwest India. Even though the POD values are showing decrease with increase in lead period of forecast, it is more than 50% for all the regions for Day 5 forecast excluding South India for which it is 45%.

VI. The CSI values are 50% or more for West, Central and Northeast India till Day 3 forecast whereas it is 50% or more for Day 1 forecast only for Northwest, South and East India.

VII. The False alarm rate is found high for D1 forecast for all the regions and it is more than 30% (34%) for East India and more than 50% (52%) for Northeast India.

VIII. Missing Rate shows lowest value for Day1 forecast after which it increases gradually. It is more than 25% for Northwest and South India with maximum for Northwest India (33%) for Day 1 forecast itself.

IX. With respect to All India sub divisional forecast, Probability of Detection, Missing rate and Critical Success Index show significant improvement of 52%, 47% and 32% respectively with respect to heavy rainfall warning issued for Day 1 during Monsoon season, when the average values of those indices for the recent period of 2017-2021 are compared with their average values for the period 2012-2016.

X. The enhancement of observational system leading to better initial conditions, improvements in Numerical Weather Prediction models and capacity building programmes extended to the forecasters leading to better understanding of the latest developments and techniques in the forecasting field gave rise to improvement in the quality of forecasts issued.

Annexure I

Heavy Rainfall and above(Monsoon Season 2021)

Station Name	June	July	August	September	Seasonal
Andaman & Nicobar Islands	5	6	8	12	31
Arunachal Pradesh	13	13	20	5	51
Assam & Meghalaya	27	24	25	8	84
NMMT	13	15	15	12	55
SHWB & Sikkim	18	20	22	6	66
Gangetic WB	12	13	11	12	48
Orissa	17	17	20	21	75
Jharkhand	16	14	9	9	48
Bihar	18	22	29	4	73
East UP	19	19	23	10	71
West UP	10	13	10	10	43
Uttarakhand	9	15	17	11	52
Haryana, Chandigarh & Delhi	0	14	10	10	34
Punjab	2	13	3	12	30
HP	5	19	15	16	55
J& K	1	14	2	2	19
West Raj	3	8	6	12	29
East Raj	9	16	14	22	61
West MP	10	19	18	23	70
East MP	14	16	15	15	60
Gujarat	13	16	6	25	60
Saurastra	6	10	2	20	38
K& Goa	23	21	11	18	73
Madhya Maharastra	14	20	11	16	61
Marathwada	9	10	6	12	37
VID	6	11	4	16	37
Chhattisgarh	17	21	16	16	70
Coastal AP	7	18	14	14	53
Telangana	15	18	16	18	67
Rayalseema	7	12	2	10	31
Tamil Nadu & Puducherry	15	22	16	20	73
C. Karnataka	14	22	10	14	60
NIK	10	10	4	7	31
SIK	15	22	16	16	69
Kerala	13	16	12	11	52
Lakshadweep	2	0	1	0	3
Total	407	559	439	465	1870

Annexure II

Very Heavy Rainfall and above (Monsoon Season 2021)

Station Name	June	July	August	September	Seasonal
Andaman & Nicobar Islands	1	4	1	5	11
Arunachal Pradesh	3	3	5	1	12
Assam & Meghalaya	14	10	16	6	46
NMMT	0	2	4	1	7
SHWB & Sikkim	8	9	14	2	33
Gangetic WB	4	7	2	5	18
Orissa	4	5	3	11	23
Jharkhand	3	2	2	2	9
Bihar	12	8	8	1	29
East UP	10	10	15	7	42
West UP	2	8	6	1	17
Uttarakhand	4	8	10	2	24
Haryana, Chandigarh & Delhi	0	7	2	6	15
Punjab	0	7	1	4	123
HP	0	6	0	3	9
J& K	0	4	0	0	4
West Raj	0	3	1	3	7
East Raj	1	7	8	6	22
West MP	3	13	8	7	31
East MP	2	6	7	4	19
Gujarat	7	7	4	13	31
Saurastra	3	4	1	9	17
K& Goa	13	14	2	11	40
Madhya Maharastra	5	13	1	5	24
Marathwada	0	3	4	5	12
VID	0	5	0	2	7
Chhattisgarh	7	7	2	4	20
Coastal AP	0	2	1	6	9
Telangana	7	10	4	7	28
Rayalseema	2	2	0	1	5
Tamil Nadu & Puducherry	6	4	2	8	20
C. Karnataka	8	17	4	3	32
NIK	3	2	0	1	6
SIK	7	10	5	6	28
Kerala	3	7	3	1	14
Lakshadweep	0	0	0	0	0
Total	142	236	146	159	683

Annexure III

Extremely Heavy Rainfall (Monsoon Season 2021)

Station Name	June	July	August	September	Seasonal
Andaman & Nicobar Islands	0	0	0	0	0
Arunachal Pradesh	0	0	0	0	0
Assam & Meghalaya	5	1	7	0	13
NMMT	0	0	0	0	0
SHWB & Sikkim	1	0	2	1	4
Gangetic WB	1	2	0	3	6
Orissa	1	0	0	2	3
Jharkhand	0	0	0	1	1
Bihar	2	0	0	0	2
East UP	2	3	0	3	8
West UP	0	1	1	0	2
Uttarakhand	1	1	2	0	4
Haryana, Chandigarh & Delhi	0	2	0	1	3
Punjab	0	0	0	0	0
HP	0	2	0	0	2
J& K	0	1	0	0	1
West Raj	0	1	1	0	2
East Raj	0	3	4	0	7
West MP	0	6	4	0	10
East MP	0	1	1	1	3
Gujarat	0	2	1	4	7
Saurastra	0	0	0	3	3
Konkan & Goa	6	8	1	3	18
Madhya Maharastra	1	5	0	0	6
Marathwada	0	0	0	0	0
VID	0	0	0	0	0
Chhattisgarh	0	0	0	0	0
Coastal AP	0	0	0	1	1
Telangana	0	3	0	2	5
Rayalseema	0	1	0	0	1
Tamil Nadu & Pudu	2	0	0	0	2
C. Karnataka	1	2	0	0	3
NIK	0	1	0	0	1
SIK	2	2	0	0	4
Kerala	0	0	0	0	0
Lakshadweep	0	0	0	0	0
Total	25	48	24	25	122

11

NOWCASTING OF THUNDERSTORMS DURING SUMMER MONSOON SEASON 2021

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11.1. Introduction :

The Monsoon season (June to September) is the main period of rainfall for much of the Indian subcontinent, with an average of 86% of the annual rainfall of India occurring during this period.Monsoon rainfall originates mainly from Mesoscale Convective Systems (MCS) which have large spatial (100s of km) and long temporal extent (many hours) (Houze et al, 2007). The MCS comprise intense convective regions, with larger regions of stratiform clouds. While the ratio of convective to stratiform regions varies across the country and whether monsoon is in active or break phase, overall the stratiform regions predominantly provide the low intensity rainfall which is characteristic of weather systems during the season (Sen Roy et al, 2015). The structure of the convective clouds varies across the country, varying from deep intense convective echoes (40 dBZ echo reaching heights >10 km) just upstream (south) of and over the lower elevations of the Himalayan barrier, to broader, less intense clouds further south (Houze et al, 2007). These broader, less intense clouds convective clouds cells over are long-lived (Sen Roy et al, 2019) and are accompanied by frequent cloud-to-ground lightning. This hazardous weather is predictable in a location specific manner only up to a few hours and has devastating potential for causing 2000-3000 human casualties every year. Fig. 11.1 illustrates the annual frequency of deaths due to lightning strikes over the Indian region from 1990 to 2020. Hence forecasting these events on short to nowcast time scales is essential for the Indian region.

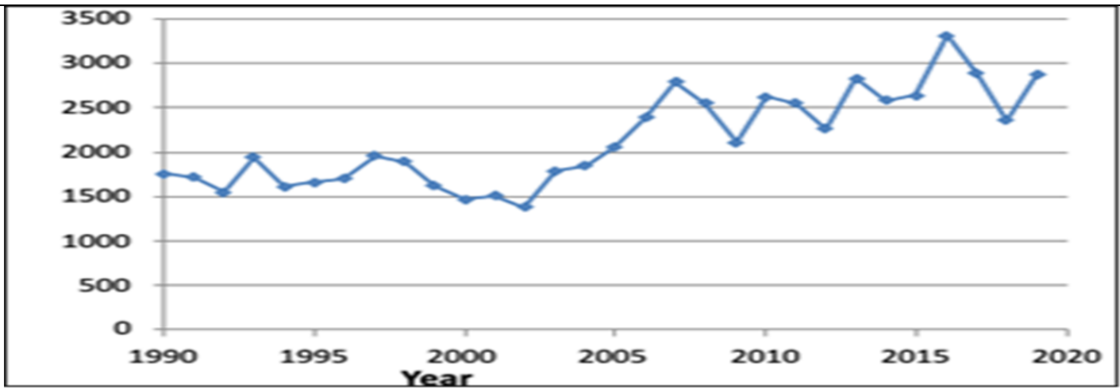

Fig. 11.1:Annual frequency of death due to lightning

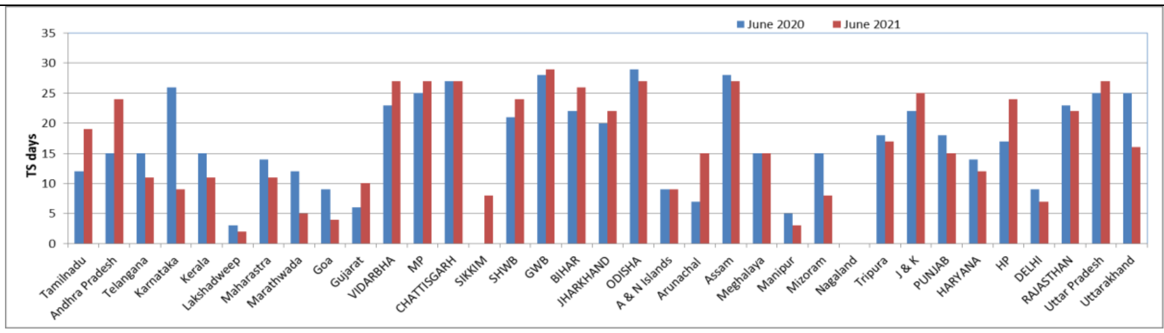

Fig.11.2 (a):Statewise Thunderstorm days recorded in June 2021 compared to June 2020

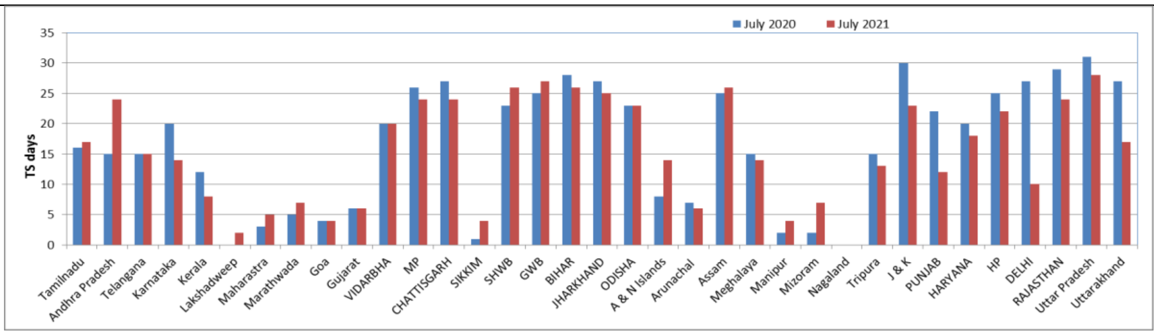

Fig. 11.2 (b): Statewise Thunderstorm days recorded in July 2021 compared to July 2020

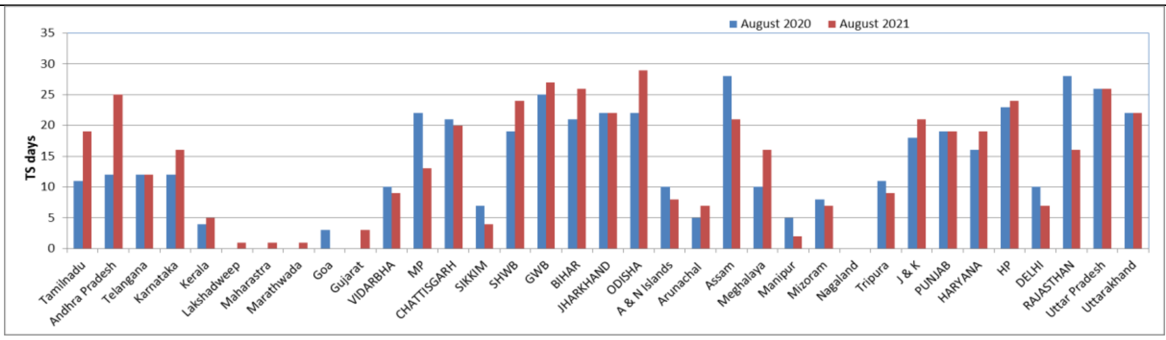

Fig. 11.2(c): Statewise Thunderstorm days recorded in August 2021 compared to August 2020

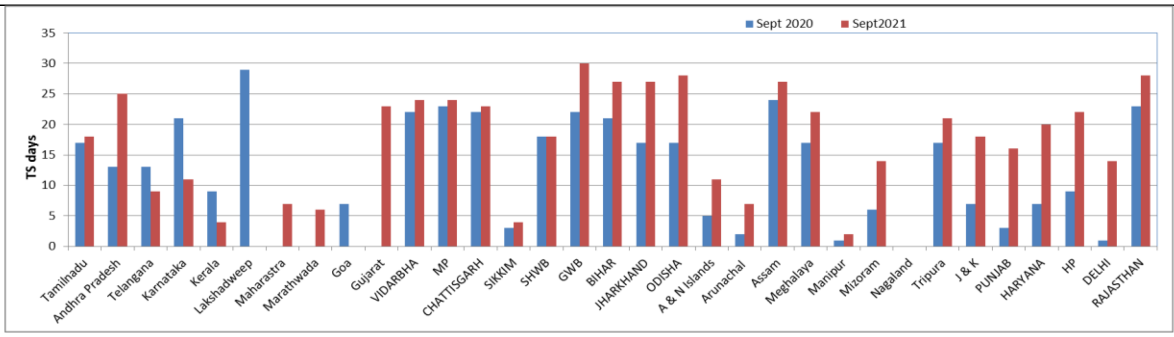

Fig. 11.2 (d): Statewise Thunderstorm days recorded in September 2021 compared toSeptember 2020

11.2: Thunderstorm occurrence over the Indian region during Monsoon 2021

Fig. 11.2 (a to d) displays the statewise record of thunderstorm days from Class I observatories of IMD during June to September 2021. With a constant observation dataset in both years, this gives an indication of distribution of thunderstorm activity over the Indian region. In June, while the thunderstorm activity over most states was comparable to the activity during 2020, thunderstorms were more frequent over Andhra Pradesh, Tamilnadu, and northwest Indian Himalayas and less frequent over southwest peninsula compared to 2020. In July, the frequency of thunderstorm days increased over northwest India but values were less compared to 2020. Higher frequency of thunderstorm days continued over southeast peninsular India. In August thunderstorm activity decreased throughout the Indian region, although the frequency of thunderstorm days was higher over southeast peninsular India compared to 2020. In September, thunderstorm activity increased and was higher for all subdivisions compared to 2020 except the western peninsula, which received far less thunderstorm activity compared to 2020.

11.3:Nowcasting Strategy for the Indian region

Since 2018, IMD issues district level nowcasts severe weather round the clock at three hour intervals for all the 732 districts of India. Nowcasts are also issued for important cities or towns which may be district headquarters or places important for tourism or commercial importance. Currently nowcasts are issued for 1089 stations around the country. Nowcasts are issued every three hours round the clock throughout the year by Meteorological Centres throughout the country. These nowcasts are displayed on an interactive map on the IMD website for district level nowcasts at (https ://mausam.imd.gov.in/imd_latest/contents/districtwisewarnings.php) and for station level nowcasts at (https://mausam.imd.gov.in/imd_latest/contents/stationwise-nowcast-warning.php).The impact expected due to the severe weather has also been added to the nowcast warnings in terms of colour codes following WMO Technical Note, 2015 (WMO. 2015) and National Disaster Management Authority (NDMA) guidelines (https://ndma.gov.in/images/pdf/Draft-Guidelines-thunderstorm.pdf) as follows:

i) **Green colour**(No severe weather)

ii) **Yellow colour**(Light rain: < 5 mm/hr/Light snow < 5cm/hr /Light Thunderstorms with maximum surface wind speed up to 40 kmph / Slight dust storm with wind speed up to 40 kmph and visibility is less than 1,000 metres but more than 500 meters due to dust / Low (< 30%) probability of cloud to ground lightning occurrence)

i) **No weather**
ii) Light rain: < 5 mm/hr
iii) Light snow < 5cm/hr
iv) Light Thunderstorms with maximum surface wind speed upto 40 kmph
v) Slight dust storm: If the wind speed is up to 40 kmph and visibility is less than 1,000 metres but more than 500 meters due to dust
vi) Low cloud to ground Lightning probability (< 30% probability of lightning occurrence)
vii) Moderate rain: 5-15 mm/hr
viii) Moderate snow: 5-15 cm/hr
ix) Moderate Thunderstorms with maximum surface wind speed between 41 – 61 kmph (In gusts).
x) Moderate dust storm: If the wind speed is between 41- 61 kmph and visibility is between 200 and 500 metres due to dust
xi) Moderate cloud to ground Lightning probability (30 - 60% probability of lightning occurrence)

xii) Heavy rain: >15 mm/hr
xiii) Heavy snow: >15 cm/hr
xiv) Severe Thunderstorms with maximum surface wind speed between 62 -87 kmph (In gusts).
xv) Very Severe Thunderstorms with maximum surface wind speed > 87 kmph (In gusts).
xvi) Thunderstorms with Hail
xvii) Severe dust storm: If surface wind speed (in gusts) exceeding 61 kmph and visibility is less than 200 metres due to dust
xviii) High cloud to ground Lightning probability (> 60% probability of lightning occurrence)
xix) Other warnings (to be filled by the user MC)
Table 11.1: Nowcast Warning categories on IMD website

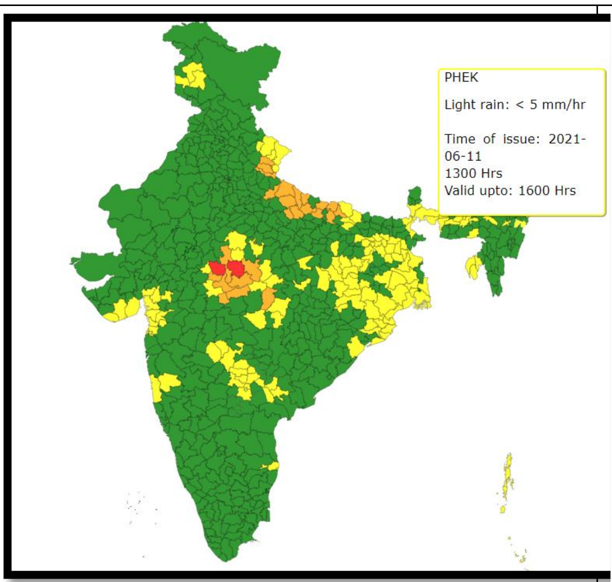

Fig. 11.3 (a): **Snapshot of District level nowcasts issued for 732 districts over the Indian region on 11 June 2021**

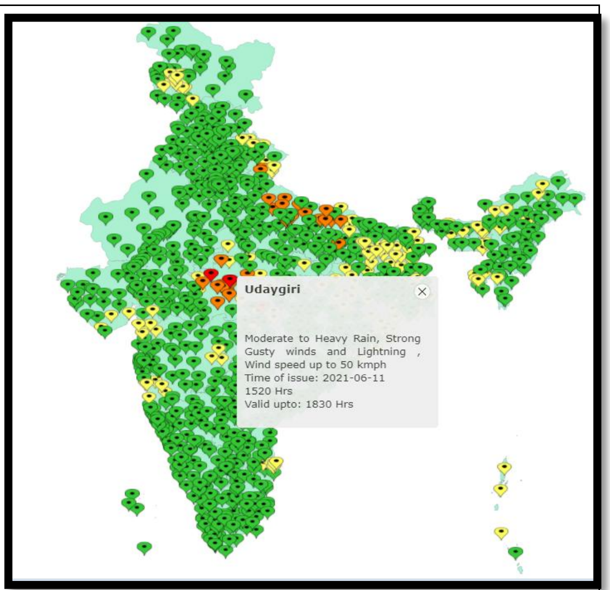

Fig. 11.3 (b): **Snapshot of Station level nowcasts issued for 1089 stations over the Indian region on 11 June 2021**

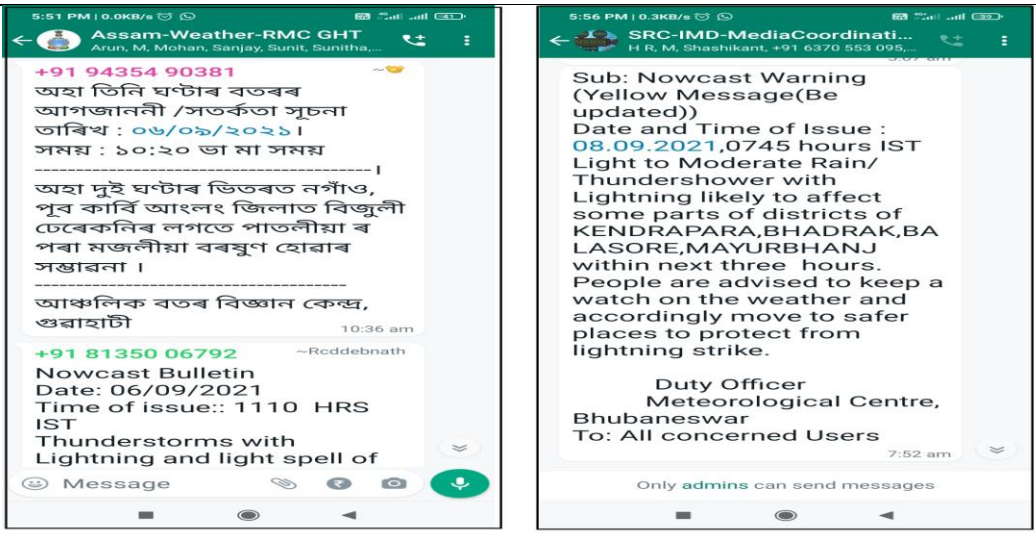

Fig.11.3 (c): Sample nowcast whatsapp messages issued during Monsoon season of 2021

iii) **Orange colour**(Moderate rain: 5-15 mm/hr /Moderate snow: 5-15 cm/hr /Moderate Thunderstorms with maximum surface wind speed between 41 – 61 kmph (In gusts) /Moderate dust storm with wind speed between 41- 61 kmph and visibility between 200 and 500 metres due to dust /Moderate (30 – 60%) probability of cloud to ground lightning occurrence)

iv) **Red colour**(Heavy rain: >15 mm/hr/Heavy snow: >15 cm/hr / Severe Thunderstorms with maximum surface wind speed between 62 -87 kmph (In gusts) / Very Severe Thunderstorms with maximum surface wind speed > 87 kmph (In gusts) / Thunderstorms with Hail /Severe dust storm with surface wind speed (in gusts) exceeding 61 kmph and visibility is less than 200 metres due to dust /High (> 60%) probability of cloud to ground lightning occurrence).

The colour coded warnings are given below in Table 11.1. Fig. 11.3 (a) and (b) display the stationwise and districtwisenowcast warnings for the Indian region.

When severe weather is expected, for maximum effectiveness of the warning, detailed SMS/Whatsapp messages and e-mails are issued to district collectors, State Disaster Management Authorities and local administration of the district concerned apart from print and electronic media. Fig. 11.3 (c) displays some sample nowcast warnings issued through whatsapp messages during Monsoon season of 2021.

11.4: Verification of Nowcasts

Thunderstorm reports from Class I observatories of IMD (about 141 stations all over India with round the clock observations), some Class II and Class III observatories that regularly report thunderstorm information, as well as observatories of the Indian Air Force are used as the observation dataset for verifying nowcasts. This total number limits realtime and near realtime thunderstorm reports to less than 150 stations all over India.For verification purposes, a yes-no criterion (2x2 contingency table) is applied for occurrence-non-occurrence of thunderstorms. When a thunderstorm report is obtained for a station within the three hour period for which thunderstorms are nowcast to occur, it is taken as a yes-yes. Similarly, the other categories of the contingency table are scored depending upon the occurrence and forecast for thunderstorms over the station. This data is used to compute various categorical skill scores in terms of (a) Probability of detection (POD) which measures the success of the forecast in correctly predicting the occurrence of thunderstorm, (b) False Alarm Ratio (FAR) which measures the number of false alarms per total number of thunderstorm predictions. (c) Critical Success Index (CSI) which is defined as the ratio of the number of hits (correct thunderstorm forecasts) to the number of events which occurred plus the number of false alarms. (d) Equitable Threat Score (ETS) which is a modification to the CSI, takes into account the number of correct forecasts of events (hits) that would be expected purely due to chance. The CSI is somewhat sensitive to the climatology of the event, tending to give poorer scores for rare events. It should be used in combination with other contingency table statistics (e.g., POD, FAR). The ETS is often used in the verification because its "equitability" allows scores to be compared more fairly across different regimes. However, it is not truly equitable. It is sensitive to hits and does not distinguish the source of forecast error and penalizes both misses and false alarms in the same way and is better for rare events (https://hwt.nssl.noaa.gov/Spring_2012/SkillScoresDescriptionSE2012.docx). For a good forecast, the FAR should approach zero and the rest of the variables should approach unity. Fig. 11.4 (a to d) display the monthwise all India skill scores of 3 hour thunderstorm nowcasts viz. POD, FAR, CSI and ETS respectively. The POD indicates gradual improvement in the detection of thunderstorms over the years.

POD scores indicate that TS nowcasts improved gradually from June to September 2021, with nearly equal scores during August and September. The FAR score decreased simultaneously with lowest values in August. Both the CSI and ETS scores gradually improved from June to August with values decreasing slightly in September.

11.5 : Conclusions

The monsoon season of 2021 was noted for delayed onset of Southwest Monsoon over northwest India. There was a long hiatus of about three weeks (19^{th} June to 11th July) before monsoon advanced to cover north/northwest India. This resulted in overall weak monsoon conditions/ over east and northeast India, West Rajasthan, Gujarat state, Kerala &Mahe and Lakshadweep, and excess rainfall over southeast and south interior peninsular India during June and July. The weather systems during the weak phase of the monsoon over north India had stronger mesoscale forcing, which resulted in thunderstorms that were small in spatial as well as temporal scale. This result is similar to previous findings on the subject (Rajeevan et al, 2013). These thunderstorms were not very well forecast by nowcasters. However, in the latter half of the monsoon season, when a large number of synoptic scale low pressure systems moved over the Indian landmass in August and September, the weather systems had larger spatial and temporal extent and were better predicted by nowcasters. Hence the forecast accuracy was higher for such weather systems.

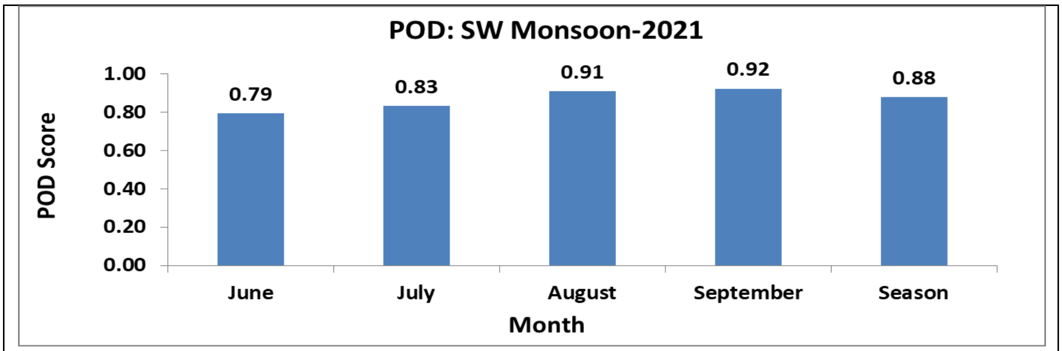

Figure 4 a: All India monthly scale POD score

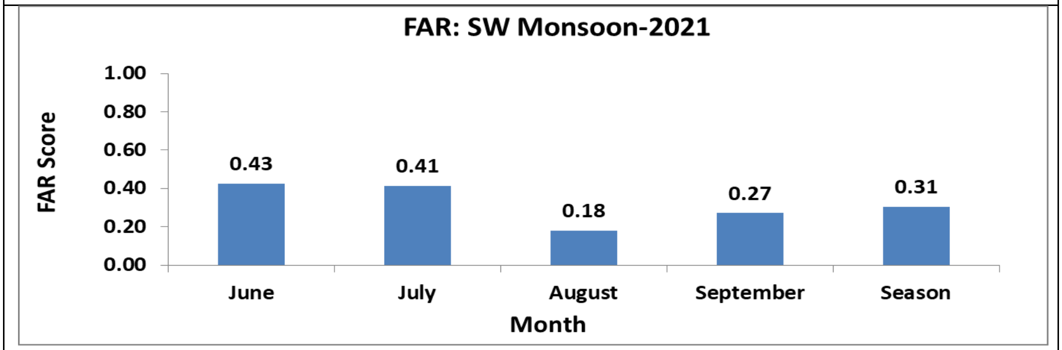

Figure 4 b: All India monthly scale FAR score

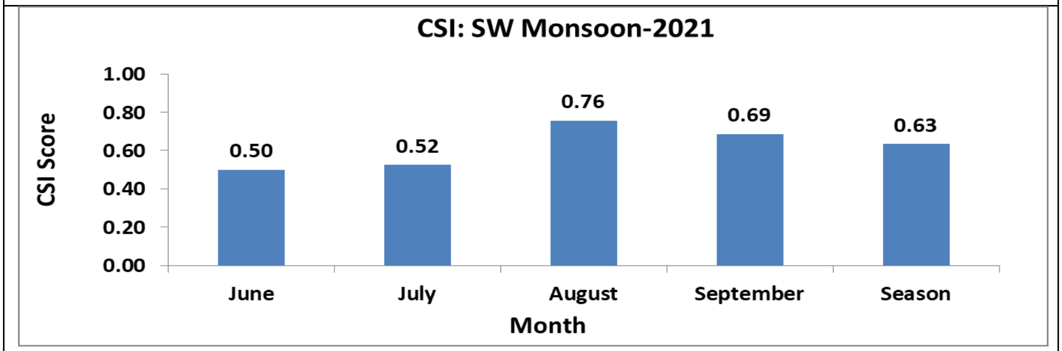

Figure 4 c: All India monthly scale CSI score

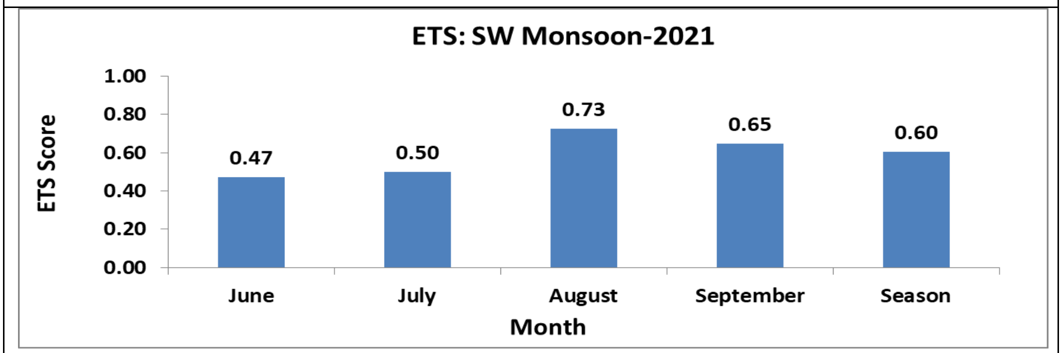

Figure 4 d: All India monthly scale ETS score

6. References :

i) Houze Jr, R.A., Wilton, D.C. and Smull, B.F., 2007. Monsoon convection in the Himalayan region as seen by the TRMM Precipitation Radar. *Quarterly Journal of the Royal Meteorological Society: A journal of the atmospheric sciences, applied meteorology and physical oceanography*, *133*(627), pp.1389-1411.

ii) Rajeevan, M., Rohini, P., Kumar, K.N., Srinivasan, J. and Unnikrishnan, C.K., 2013. A study of vertical cloud structure of the Indian summer monsoon using CloudSat data. *Climate dynamics*, *40*(3-4), pp.637-650.

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iv) Sen Roy, S., Saha, S.B., Bhowmik, S.R. and Kundu, P.K., 2019. Diurnal variability of convection over northwest Indian subcontinent observed by the Doppler weather radar data. *Meteorology and Atmospheric Physics*, *131*(5), pp.1577-1604.

12

MARINE WEATHER FORCASTING DURING SOUTH WEST MONSOON SEASON 2021

12.1: Introduction

The bulletins and warnings issued in the interest of Mariners by India Meteorological Department are: (i) Sea Area bulletins [for shipping on high seas and for ships plying in coastal waters (unto 75 Kms off the coastline)], (ii) Bulletins for Indian Navy, (iii) Port warnings, (iv) Fisheries warnings (Text as well as graphical form), (v) Fourstagewarnings for Cyclones, (vi) Bulletinsfordepartmentalexchanges, (vii) Portwarnings, (viii) BulletinforAIR, (ix) WarningsforDesignated/Registeredusers, and BulletinsforPress.

12.2: The offices and areas of responsibility

All the bulletins and warnings for mariners are being issued by the three ACWCs at Mumbai, Chennai and Kolkata. However, the bulletins and warnings for high seas, including GMDSS are issued by ACWC Mumbai (for Arabian Sea) and ACWC Kolkata (for Bay of Bengal) only in the Fig.12.1.

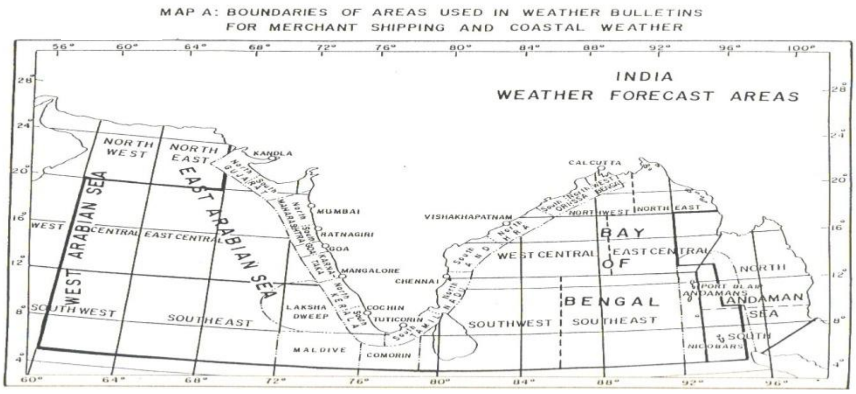

Fig. 12.1: The marine weather forecast areas under IMD are as in the map

12.3: GMDSS

Under Global Maritime Distress Safety System (GMDSS) scheme, India has been designated as one of the 16 service providers in the world for issuing Sea area bulletins for broadcast through GMDSS for MET AREA VIII (N), which covers a large portion of north Indian Ocean. As a routine, two GMDSS bulletins are issued at 0900 and 1800 UTC. During cyclone situations, additional bulletins (upto 4) are issued for GMDSS broadcast in the Fig.12.2.

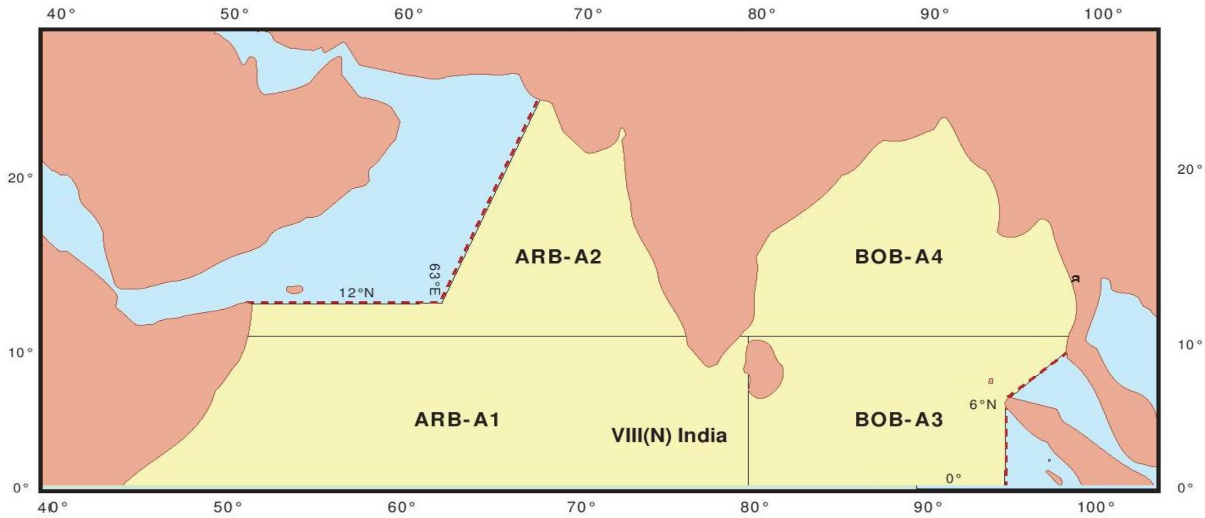

Fig.12.2 The area of responsibility for GMDSS forecast is given in the map.

The GMDSS bulletins are prepared by ACWC (Area Cyclone Warning Centre) Mumbai for the Arabian Sea, by ACWC Kolkata for Bay of Bengal and by RSMC, New Delhi for Indian Ocean, north of Equator upto 5°N, for their areas of responsibility. The bulletins are compiled by RSMC, New Delhi and the final bulletin is transmitted to communication division for further transmission to LES Delhi (Noida).

12.4: Marine Weather Forecasting during Southwest Monsoon 2021

Winds are the driving force of weather at sea. Wind generates local wind waves and swells. Hence forecast of wind direction, weather and sea state is extremely important for mariners. Monsoon circulations being mostly wind driven, forecast of wind speed, direction and weather, issue of fishermen and port warnings during active monsoon conditions and formation of low-pressure systems are also of extreme importance.

12.4: Marine Weather Forecasting over Arabian Sea

RWFC Mumbai has the mandate for providing marine forecasts for Arabian Sea within its area of responsibility north of Latitude 5^0 Northupto the north coast and east of longitude 60^0 Eastupto the western coast. Following are different marine forecasts being issued:

- **Coastal Bulletins**: Issued twice a day for the coastal area (75 Km from the coast line). These are for the benefit of ships sailing close to the coast. It contains information about wind visibility weather and state of sea.
- **Sea Area Bulletins**: Issued twice a day for merchant ships plying in high seas. They comprise inference of the sea area, sector wise forecast of wind direction & speed, visibility and weather.
- **GMDSS Bulletins:**ACWC Mumbai issues bulletins for the Persian Gulf, North Arabian Sea and portions of Indian Ocean E00, E05 (as shown in the map).
- **Fleet Forecast:** This is issued for Indian navy and contains same information as the sea area bulletin with more resolution.

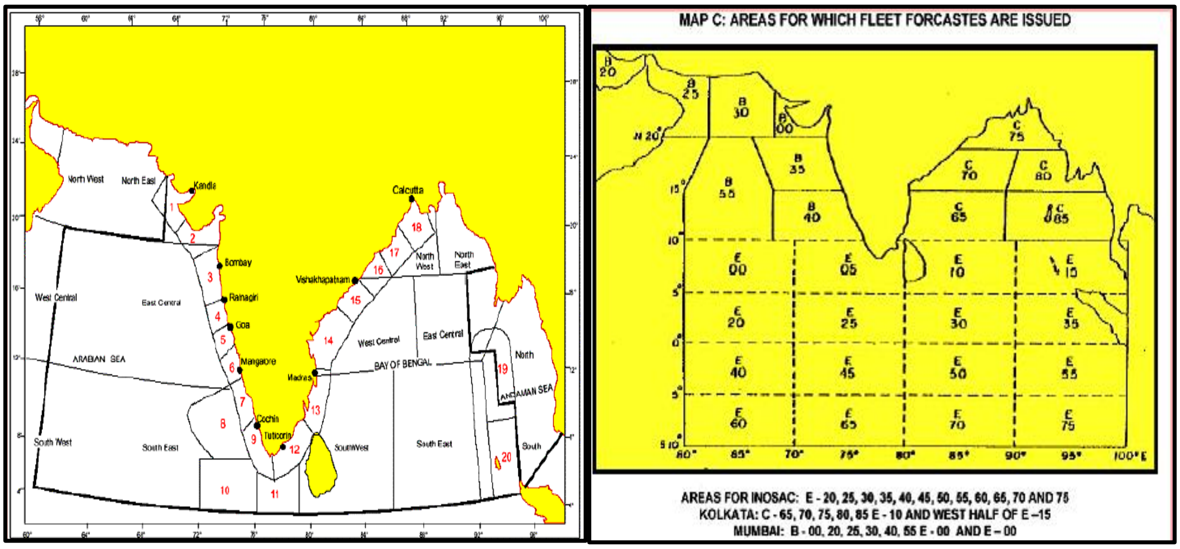

Fig.12.3. Area of responsibility over Arabian Sea and Bay of Bengal

12.5.1:Progress of South West Monsoon over Arabian Sea during 2021

South west monsoon 2021started its progress into South Arabian Sea around 3rd June. It further continued its progress into Central Arabian Sea around 5th June. Arabian Sea branch of monsoon progressed very quickly during the subsequent week and covered entire Central Arabian Sea by 9thJune. By 10th June south west monsoon currents further marked its progress into northeast and northwest Arabian Sea. South West Monsoon covered entire north Arabian Sea by 19th June 2021 in Fig.12.3.

12.5.2:Cyclonic disturbances in Arabian Sea

No intense low-pressure systems formed over Arabian Sea during the major partof monsoon season. However, towards the withdrawal phase of south west monsoon, the remnant of cyclonic storm Gulab emerged as a well-markedlow-pressure area into south Gujarat region & adjoining Gulf of Khambhaton 29thSeptember. It concentrated into a depressionover northeast Arabian Sea & adjoining Kutch, on 30thSeptember. It moved westwards and intensified into cyclonic storm “**Shaheen**” overthe northeast Arabian Sea off Gujarat coast on1st October,2021. It furtherintensified into asevere cyclonic storm in the evening of 1stOctober over northwest &adjoining northeast Arabian Sea. Continuing to move westwards, it recurved west-southwestwards and crossed Oman coast during 0030-0130 IST of 4thOctober.

12.5.3:Intensity/Strength of South West Monsoon over Arabian Sea

Intensity/strength of south west monsoon over sea area is classified as weak, moderate, strong and vigorous depending on the wind speed observed. Accordingly, the classification is as follows:

- Weak : Up to 12knots
- Moderate : 13-22 knots
- Strong : 23-32 knots
- Vigorous : 33 knots and above

Strength of south west monsoon during June – September over different sectors of Arabian Sea is described below:

It was observed that during most days of June, monsoon remained moderate to strong over South West and adjoining West Central Arabian Sea due to strong cross equatorial flow. Strength/intensity of monsoon remained moderate over South east Arabian Sea and North Arabian Sea on most days during the month of June.

Strength of monsoon was found to increase in the month of July over entire Arabian Sea with the overall strengthening of cross equatorial flow. Strong monsoon conditions were observed over West Central and South West Arabian Sea. Vigorous monsoon condition was observed during a few occasions in association with further strengthening of cross equatorial flow. Monsoon remained moderate over North East and East Central Arabian Sea on most days of July.However, in association with cyclonic circulations in East Central and north Arabian Sea, off shore trough and east west shear zones, strong monsoon conditions (with wind speed between 23-32 knots) were observed over the region on a few occasions.Monsoon remained moderate over South East Arabian Sea on most of the days during July.

Strength of monsoon during August was observed to be weaker compared to July over entire Arabian Sea. First half of August month continued to remain similar to July over all sectors of Arabian Sea. But during latter half of the August, weak to moderate monsoon conditions were observed South East and North East Arabian Sea; andmoderate to sometimes strong monsoon conditions prevailed over rest of the sectors of Arabian Sea.

Moderate to strong monsoon intensity prevailed over South west and adjoining west Central Arabian Sea during most days of September. Weak to moderate monsoon conditions prevailed over North Arabian Sea, East Central Arabian Sea and South East Arabian Sea during most occasions. However strong monsoon conditions were observed over North Arabian Seaduring the last week of September in association with the emergence of the remanent of cyclonic storm “Gulab” into North Arabian Sea and its further intensification into severe cyclonic storm “Shaheen”.

Among the different sectors of Arabian Sea, monsoon intensity was observed to be maximum over South West Arabian Sea and West Central Arabian Sea with moderate to strong monsoon over most of the occasions. South east sector of Arabian Sea was observed to have lowest monsoon intensity throughout monsoon 2021.

12.6:Marine Weather Forecasts Issued from ACWC Mumbai

Statistics of bulletins issued during 2021 south west monsoon season (June-September) issued by ACWC Mumbai as part of marine weather forecast is given below.

S.No.	Type of Bulletin	No. of bulletins issued
1.	**Sea Area Bulletins** (Issued twice daily Aurora & Balloon based on 03 UTC &12 UTC Charts respectively and extra bulletins during depression and cyclonic storms)	245
2.	**CoastalWeather Bulletins** (Issued twice daily: Daily I & Daily II issued at 12:30 IST and 21:00 IST respectively)	244
3.	**Fleet Forecasts** (Issued twice daily)	244
4.	**Fishermen Warnings issued for Maharashtra Goa coasts** (Issued and updated 4 times daily)	Issued for North Maharashtra coast on 58 occasions. Issued for South Maharashtra – Goa coast on 52 occasions
5.	Port warnings (Issued and updated 4 times daily).	Port warnings were issued on 4 occasions for Maharashtra- Goa coast.

2.7 Marine Weather Forecasts Issued from ACWC Kolkata :

Statistics of bulletins issued during 2021 south west monsoon season (June-September) issued by ACWC Kolkata as part of marine weather forecast is given below.

S.No.	Type of Bulletin	No. of bulletins issued
1.	**Sea Area Bulletins** (Issued twice daily Aurora & Balloon based on 03 UTC & 12 UTC Charts respectively and extra bulletins during depression and cyclonic storms)	298
2.	**Coastal Weather Bulletins** (Issued twice daily: Daily I & Daily II issued at 12:30 IST and 21:00 IST respectively)	298
3.	**Fleet Forecasts** (Issued twice daily)	298
4.	**Fishermen Warnings issued for West Bengal and Andaman coasts** (Issued and updated 4 times daily)	Issued for West Bengal coast on 116 occasions. Issued for Andaman coast on 126 occasions
5.	Port warnings (Issued and updated 4 times daily).	Port warnings were issued on 15 occasions for West Bengal coast and on 09 occasions for Andaman coast.

12.8 : Marine Weather Forecasts Issued from ACWC Chennai

Statistics of bulletins issued during Southwest monsoon season (June-September) 2021 issued by ACWC Chennai as part of marine weather forecast is given below.

S.No.	Type of Bulletin	No. of bulletins issued
1.	**Sea Area Bulletins** (Issued twice daily Morning inference & Evening inference based on 03 UTC & 12 UTC Charts respectively)	244
2.	**Coastal Weather Bulletins** (Issued twice daily: Daily I & Daily II issued at 14:00 IST and 21:00 IST respectively).	244
3.	**Fishermen Warnings issued for Tamil Nadu, Puducherry &Karaikal coast.** (Issued and updated 4 times daily).	Issued for Tamil Nadu, Puducherry and Karaikal coast on 180 occasions.
4.	Port warnings (Issued and updated 4 times daily)	Port warnings were issued on 6 occasions for Tamil Nadu, Puducherry and Karaikal ports.

13

Summary and Conclusions

This report consists of 13 Chapters, including this chapter and discussed various important aspects of southwest monsoon during 2021.

The information related to the regional Characteristics of the Southwest Monsoon such as monsoon onset over Kerala, its further progress over the remaining part of the country and withdrawal has been given in the Chapter 1. Southwest monsoon set in over Kerala on 3rd June, 4 days delay in onset than normal. Gradual advancement of monsoon happened over many places up to central India. Further advanced into most parts of Rajasthan, Punjab; some more parts of Haryana and West Uttar Pradesh on 12th July after a hiatus of about three weeks. It then covered the remaining parts of Punjab, Haryana and Rajasthan and thus the entire country on 13th July, against the normal date of 8th July. This monsoon season witnessed the formation of two cyclonic storm and one system reached DD category, all the systems are formed during September month. Though the frequency of cyclonic storms is less during the southwest monsoon period, there had been 5 more such years in the recent 30 years. Withdrawal of 2021 southwest monsoon season starts on 6th October against its normal date 17th September, due to formation of frequent low pressure systems and the prevalence of an active Inter Tropical Convergence Zone, across central India, north Indian Ocean. Southwest monsoon withdrew on a rapid phase from the entire country by 25th October (against the normal date of 15th October). The season had several record-breaking extreme rainfall and resultant Flood events caused human casualty and property damage in many parts of the country. The season also witnessed severe thunderstorm activity and associated with loss of life in Madhya Pradesh in July *month*.

Chapter 2 discussed global climate anomalies observed during 2021 monsoon season. The season starts with Neutral ENSO condition over the west Pacific. As a result, influence on the monsoon from the large-scale SST forcing from Pacific Ocean was very clear during beginning of the season especially in the month of June. The Indian Ocean Dipole (IOD) was negative throughout the monsoon season with significantly below normal SSTs over equatorial East Indian Ocean. The large rainfall deficiency in August month mainly due to the development of negative IOD. The development La Nina conditions over the Pacific ocean and formation of many low-pressure system in September resulted increase rainfall activity during end of monsoon season.

Chapters 3 provide details of significant weather events occurred at various parts of the country during the 2021 SW Monsoon season. Description of Various synoptic scale systems associated with heavy rainfall events also given in the chapter.

The rainfall features observed during 2021 monsoon season were described in Chapter 4. The Southwest Monsoon season rainfall over the country as a whole during 2021 was normal (99% of Long Period Average (LPA)). Rainfall distribution was generally well distributed over major parts of the country. The SW monsoon season observed significant intra seasonal variations in rainfall as realized rainfall in June (110 % of LPA), July (93 % of LPA) and August (76 % of LPA) while it was the highest during September (135 % of LPA). The homogeneous regions of Northwest India (96% of LPA) and Central India (104% of LPA) received normal rainfall. However, South Peninsula (111% of LPA) received above normal rainfall, while the homogeneous region of East & Northeast India (88% of LPA) received below normal rainfall. Out of the total 36 meteorological subdivisions, 20 subdivisions constituting 58% of the total area of the country received normal seasonal rainfall, 10 subdivisions received excess rainfall (25% of the total area) and 6 subdivisions (17% of the total area) received deficient season rainfall. These 6 Met subdivisions which got deficient rainfall are Nagaland, Manipur, Mizoram & Tripura, Assam and Meghalaya, Arunachal Pradesh, Jammu & Kashmir and Ladakh, West Uttar Pradesh and Lakshadweep. Out of these six Subdivisions, three subdivisions in northeast India. Two Met Subdivisions which got much higher than normal rainfall in the season are Marathawada and Telangana.

Chapters 5 describe performance of various NWP model products used for short and medium range forecast during 2021 monsoon season operational forecast verification of GFS and WRF model products. The detailed assessment of performance of global model (GFS T1534L64 v14) and mesoscale model (WRF) model operational at IMD over Indian region in spatial and temporal scale during summer monsoon season of 2021 are given in the chapter. IMD-WRF model forecast is evaluated during the South West monsoon period of 2021. Model is able to represent general characteristics of rainfall in all the months. There is a systematic overestimation of rainfall over West coast of India and North East India in all the months. It is seen that model has good skill in the forecast of light to moderate rainfall while in forecast of heavy rainfall model skill is poor. In mean characteristics of rainfall day1 forecast show better match with observed rainfall than forecasts of longer lead times which is more evident in the months from June to August.

Chapter 6 describes operational and experimental extended range forecast during the monsoon season. The real time extended range forecast during different phase of monsoon 2021 have captured the observed intra-seasonal variability very well with 2 to 3 weeks lead time for all the target weeks covering active, weak, transition phases of monsoon and the delayed withdrawal of monsoon from northwest India. Quantitatively, the ERF performance for the entire monsoon season of 2021 for 18 weeks period show very skillful prediction with the extended range forecast of rainfall has been captured very well like the observed rainfall departure during the different phases of monsoon. Significant correlation coefficients up to 4 weeks lead time between observed and forecast rainfall departure on all India time scale is noticed. The active phase of monsoon during September leading to delayed withdrawal of monsoon from northwest India was well predicted in the ERF with 3 weeks lead time. Over the homogeneous regions it is observed that the CC is significant (95% level) between forecast and observed rainfall departure over the CE India and NW India for forecasts up to three weeks. However, the CC is significant only in week 1 forecast over the NE India and SP India. .

Chapter 7 discussed the verification of operational and experimental long range forecast during the 2021 monsoon season. it was predicted on 15th May 2021 that monsoon will set in over Kerala on 31st May with a model error of ±4 days. However, the actual monsoon onset over Kerala took place on 3rd June within limit of model error of ±4 days and therefore the forecast was correct. IMD has adopted a new strategy for issuing monthly and seasonal operational forecasts for the southwest monsoon rainfall over the country by modifying the existing two stage forecasting strategy. The new strategy is based on the existing statistical forecasting system and the newly developed Multi-Model Ensemble (MME) based forecasting system. The spatial tercile probability forecast for rainfall also issued based on MME. Addition to that monthly rainfall over the country as a whole for the months of June, July, August, September & second half of the season (Aug-Sept) were issued. IMD has also issued a separate forecast for the Monsoon Core Zone (MCZ) in addition to the four homogeneous region. The first stage forecast for the season (June-September) rainfall over the country as a whole issued in April was 98% of LPA with a model error of ± 5% of LPA. The update issued in May for this forecast was (101% of LPA) with a model error of ± 4% of LPA. The actual season rainfall for the country as a whole was 99% of LPA, which is within the forecast limits of the April and May forecasts. Thus, the both the forecasts were within the forecast limits. Most of the operational forecast was within the limit forecast except the forecast issued for August. IMD forecast correctly indicated the devolvement of negative Indian Ocean Dipole (IOD) during the 2021 monsoon season.

The analysis of features of 2021 southwest monsoon season using various satellite data products were given in chapter 8. The monsoon season of 2021 was characterized by two cyclones each at the onset and the withdrawal period. “TAUKTAE”, over the Arabian Sea (14th to 19th May) and severe Cyclonic storm “YAAS” over Bay of Bengal (23rd to 28th May) formed during the onset phase of monsoon. The withdrawal period also witnessed the formation of a monsoon depression and a cyclonic storm “GULAB” in the month of September. The chapter also describe various features of these synoptic system in details. The detailed information about the satellite observation of very severe cyclonic storms formed over North Indian Ocean during the monsoon season also given in the chapter.

The details of the agrometeorological services provided during the monsoon season were given in Chapter 9. IMD issued appropriate measures to farming community through the agromet advisories based on the medium range weather forecast as well as the extended range weather forecast in order to deal with the impact of adverse weather situation. These advisories have helped the farmers to undertake decisions on sowing of crops, supplementary irrigation, pest and disease control, contingent crop planning etc. in time which has resulted in improvement in agricultural situations under extreme weather conditions. Temporal and spatial distribution of rainfall during southwest monsoon season in 2021 impacted the crop production across the country.

Chapter 10 describes the verification of Heavy rainfall Warnings issued by IMD during Monsoon season 2021. The Probability of Detection, Critical Success Index, False Alarm Rate and Missing Rate are computed regional wise as well as All India basis for the sub divisional forecast and the results are compared. The average values of verification indices for Day 1 forecast (All India Warning) for the period 2012-2016 are compared with that for the period 2017-2021 and the results are presented. The verification of forecast issued for 1870 events of heavy rainfall and above during Monsoon season 2021 out of which 683 had been very heavy rainfall and above and 122 had been extremely heavy rainfall. The maximum events of heavy rainfall and above, very heavy rainfall and above and extremely heavy rainfall had occurred in the month of July. The deatiled information of verification of forecast for various regions also given in the chapter.

The detailed analysis of Nowcasting of thunderstorms during Summer Monsoon Season 2021 are given in chapter 11.The monsoon season of 2021 was noted for delayed onset of Southwest Monsoon over northwest India. There was a long hiatus of about three weeks (19th June to 11th July) before monsoon advanced to cover north/northwest India. The weather systems during the weak phase of the monsoon over north India had stronger mesoscale forcing, which resulted in thunderstorms that were small in spatial as well as temporal scale. These thunderstorms were not very well forecast by nowcasters. However, in the latter half of the monsoon season, when a large number of synoptic scale low pressure systems moved over the Indian landmass in August and September, the weather systems had larger spatial and temporal extent and were better predicted by nowcasters. Hence the forecast accuracy was higher for such weather systems.

Chapter 12 describe the various marine weather forecast issued during south west monsoon season 2021.